EXPERIMENTAL OVERVIEW

FOR e^+e^- LINEAR COLLIDERS NEAR FUTURE

29. 4. 99

LCWS99, SITGES SPAIN

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LC PHYSICS

ELEMENTARY PARTICLE PHYSICS
IS ALMOST AT ITS TURNING POINT.
THE KEY IS THE LIGHT HIGGS BOSON.

$\exists$ LIGHT HIGGS BOSON)

$\Rightarrow$ HIGGS IS ELEMENTARY
SUPERSYMMETRY + GUT
(SUSY BREAKING MECHANISM ?)
$\downarrow$
SUPERSTRING (GEOMETRY)

$\nexists$ LIGHT HIGGS BOSON)

$\rightarrow$ COMPOSITE HIGGS ?
NEW STRONG INTERACTION
@ TeV SCALE.

(AT THE MOMENT THERE ARE
NO REALISTIC MODELS
WALKING T.C. TOP CONDENSATION
...)

$\Rightarrow$ **NEW PARADIGM** IN $\lesssim$ 10 YEARS

Experimental Indication of M_H

presented by [illegible] Karlen at ICHEP 98, Vancouver, July,1998

Global electroweak fit using as input:

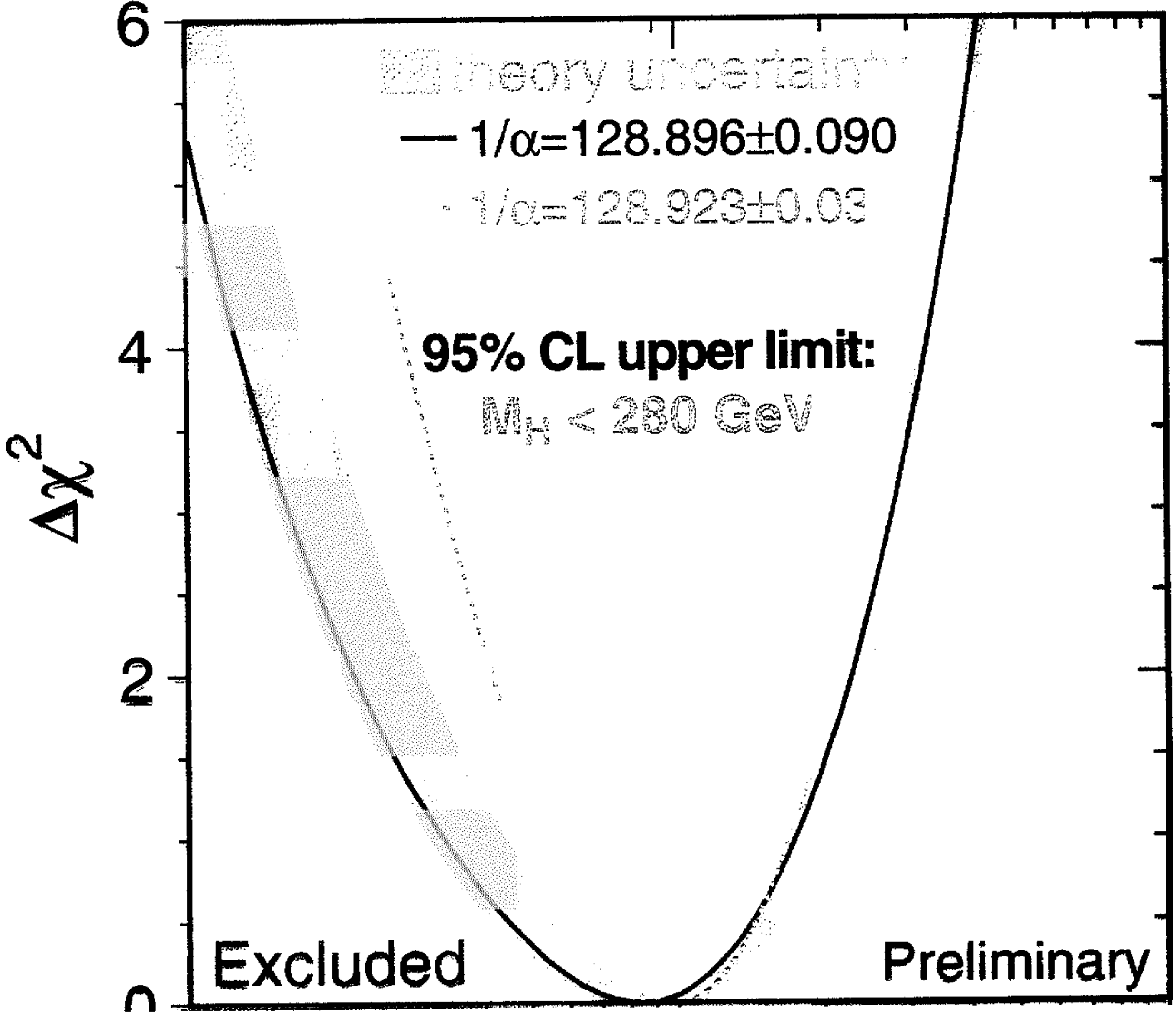
(1) Z^0 measurements from LEP/SLC, m_W from LEP2 and Tevatron

(2) $\sin^2\theta_W$(on-shell) = 0.2255 ± 0.0021 (NuTeV and CCFR)

(3) m_t = 173.8 ± 5.0 GeV (CDF and D0)

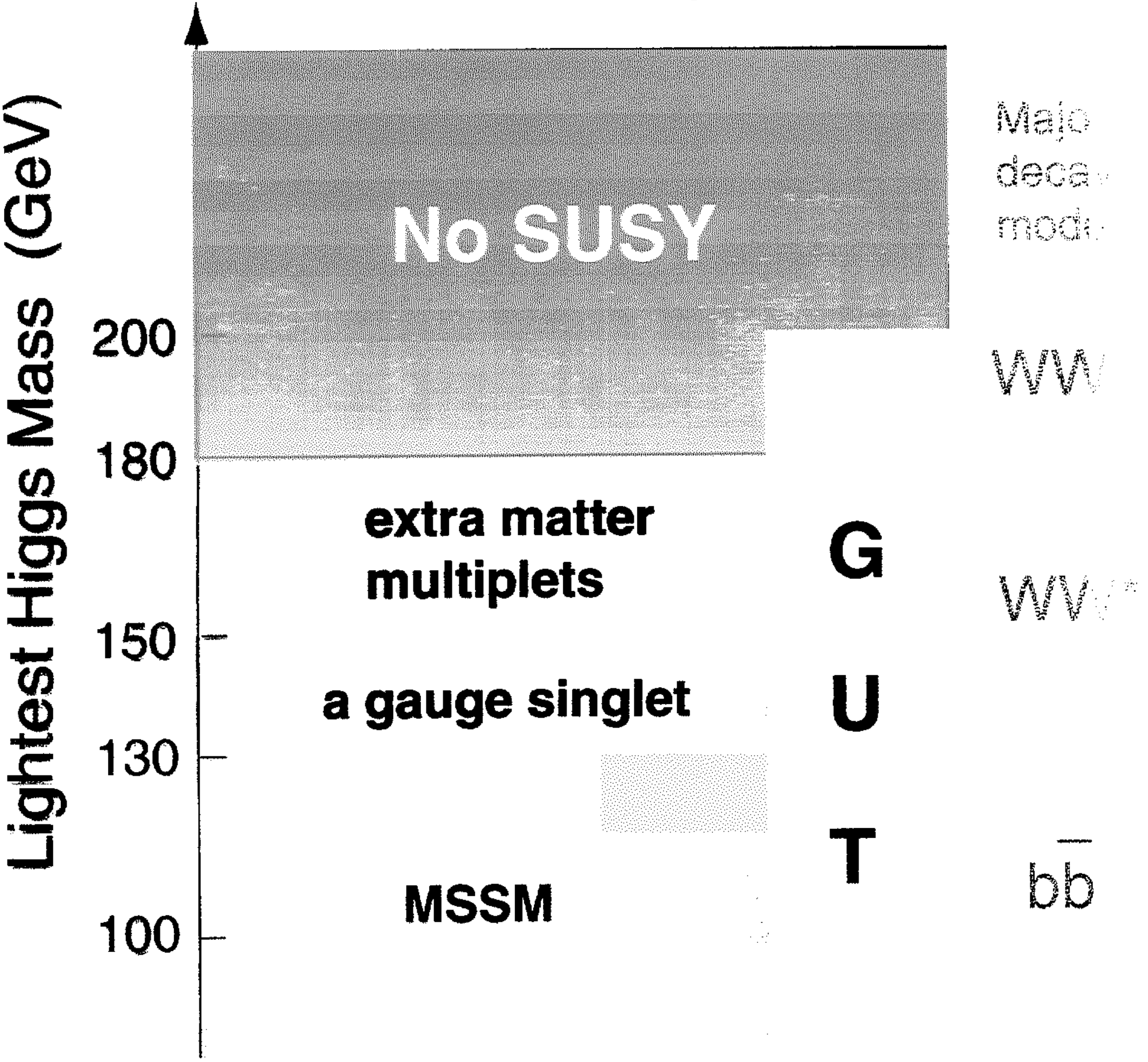
(4) $1/\alpha(m_Z)$ = 128.896 ± 0.090

LEP Electroweak Working Group, summer 1998



Upper Bound of Lightest SUSY-Higgs Mass

ref. T.Moroi, Y.Okada, Physics Letters B**295**(1992)73-78



LHC (+LEP2) ALONE CANNOT EXPLORE ALL THE ESSENTIAL PHYSICS.

- **HIGGS SECTOR**

THE LIGHT HIGGS CAN BE DISCOVERED AT LEP2.

STATISTICS IS NOT ENOUGH TO STUDY ANY DETAILS.

AT LHC, UNDERSTANDING OF DETECTORS AND BACKGROUND MAY TAKE LONG TIME.

LARGE tanβ LARGE MA REGION IS LEFT FOR LHC (IN MSSM).

$\sigma(h) B(h \to \gamma\gamma)$ ~ 5 fb $m_A = 150$ GeV

~ 50 fb $m_A = 500$ GeV

$\sigma(Wh) B(h \to \gamma\gamma) P(\geq 1 W \to \ell\nu)$

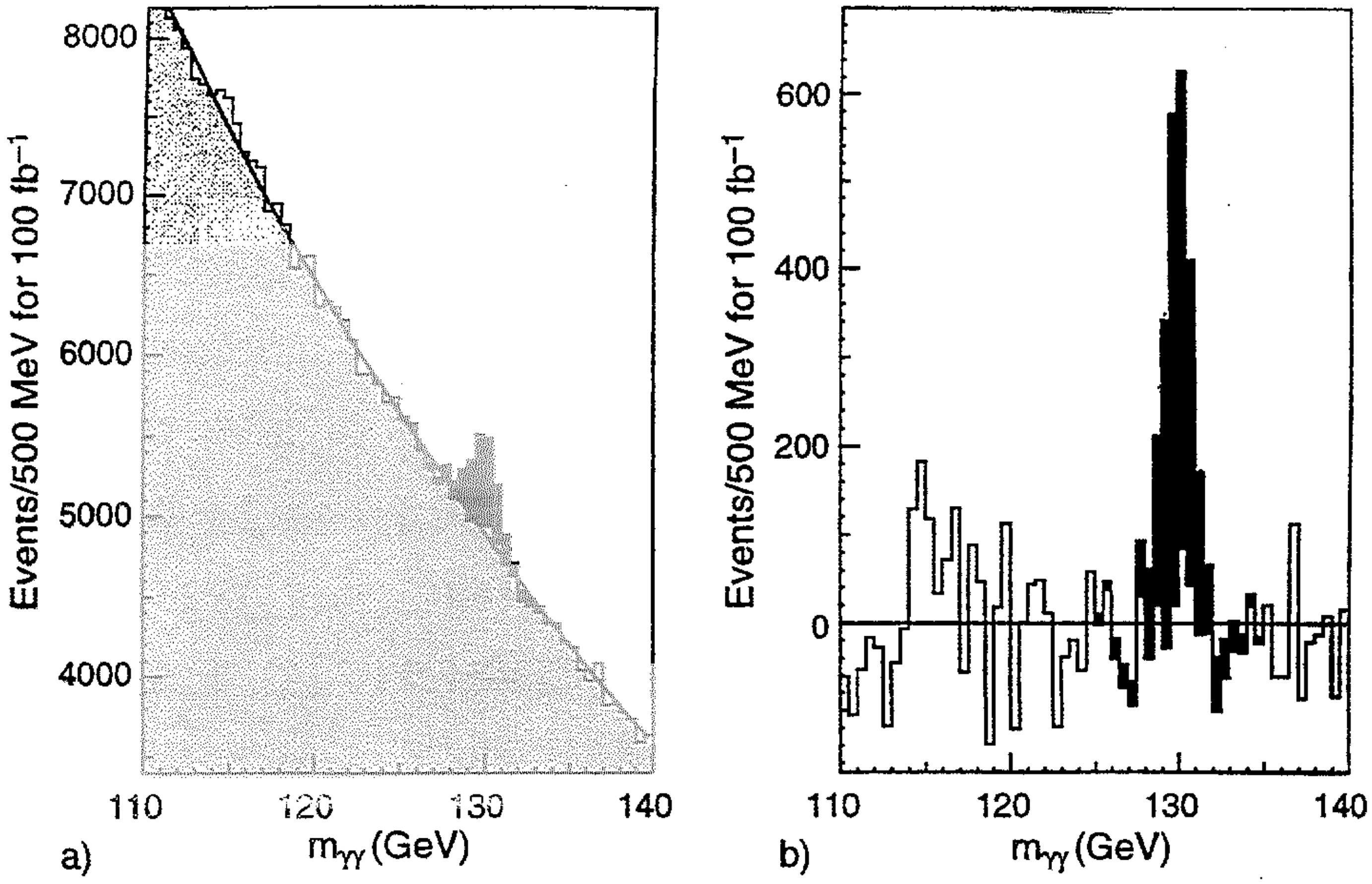
~ 1.4 fb $m_A = 500$ GeV

$\sigma($[illegible] $A,$ [illegible] $H)\ B(A, H \to$ [illegible]$)$

~ 300 fb $m_A = 300$ GeV $\tan\beta = 10$

~ 2.5 pb $m_A = 300$ GeV $\tan\beta = 30$

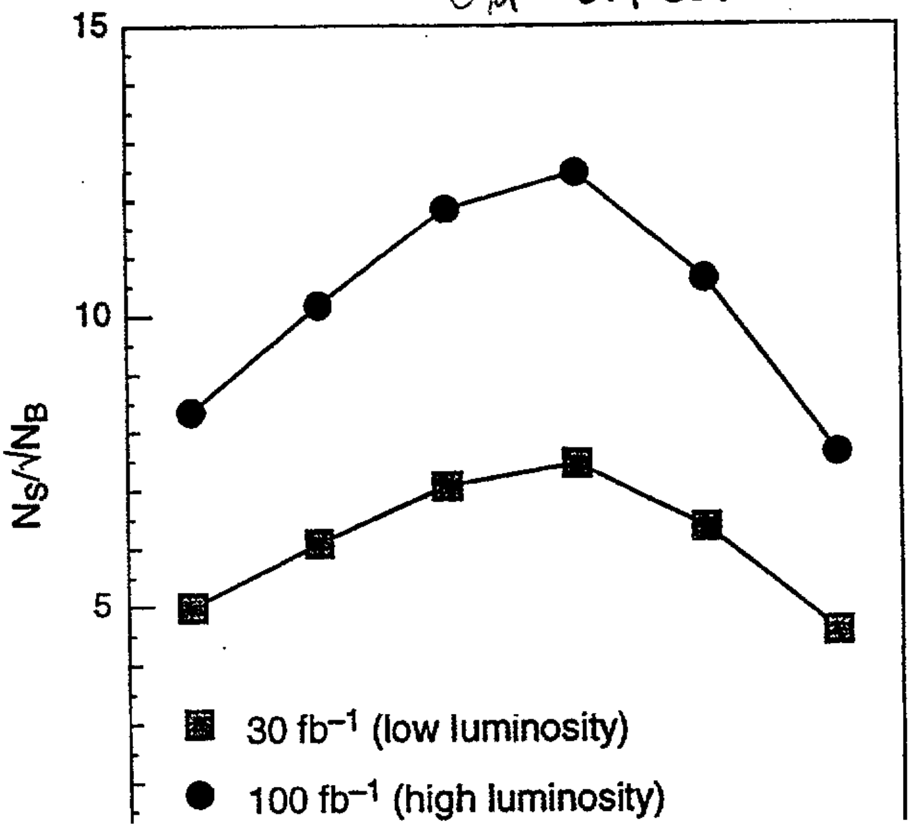
$\sigma(Wh) B(h \to b\bar{b}) B(W \to \ell\nu)$

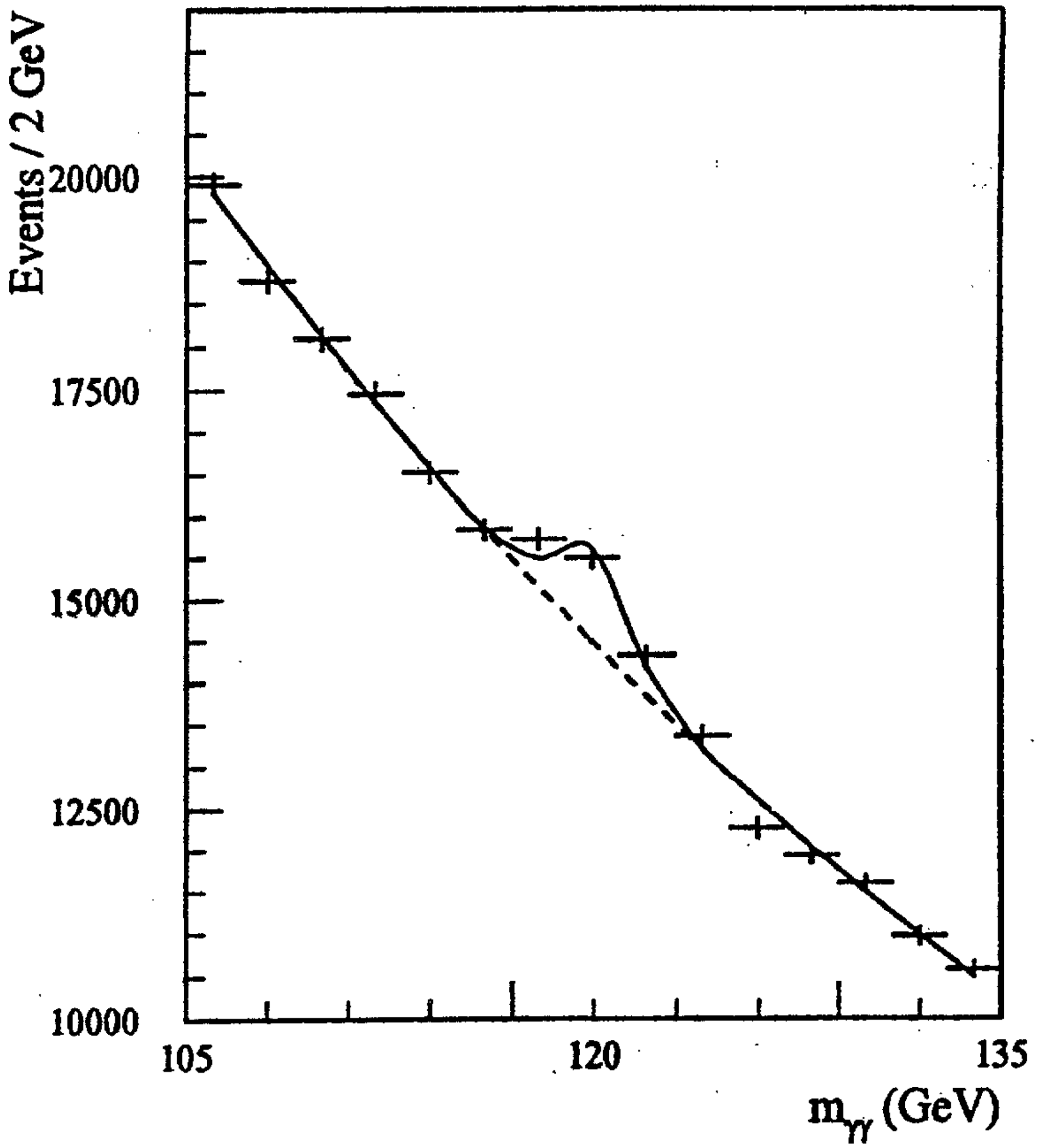


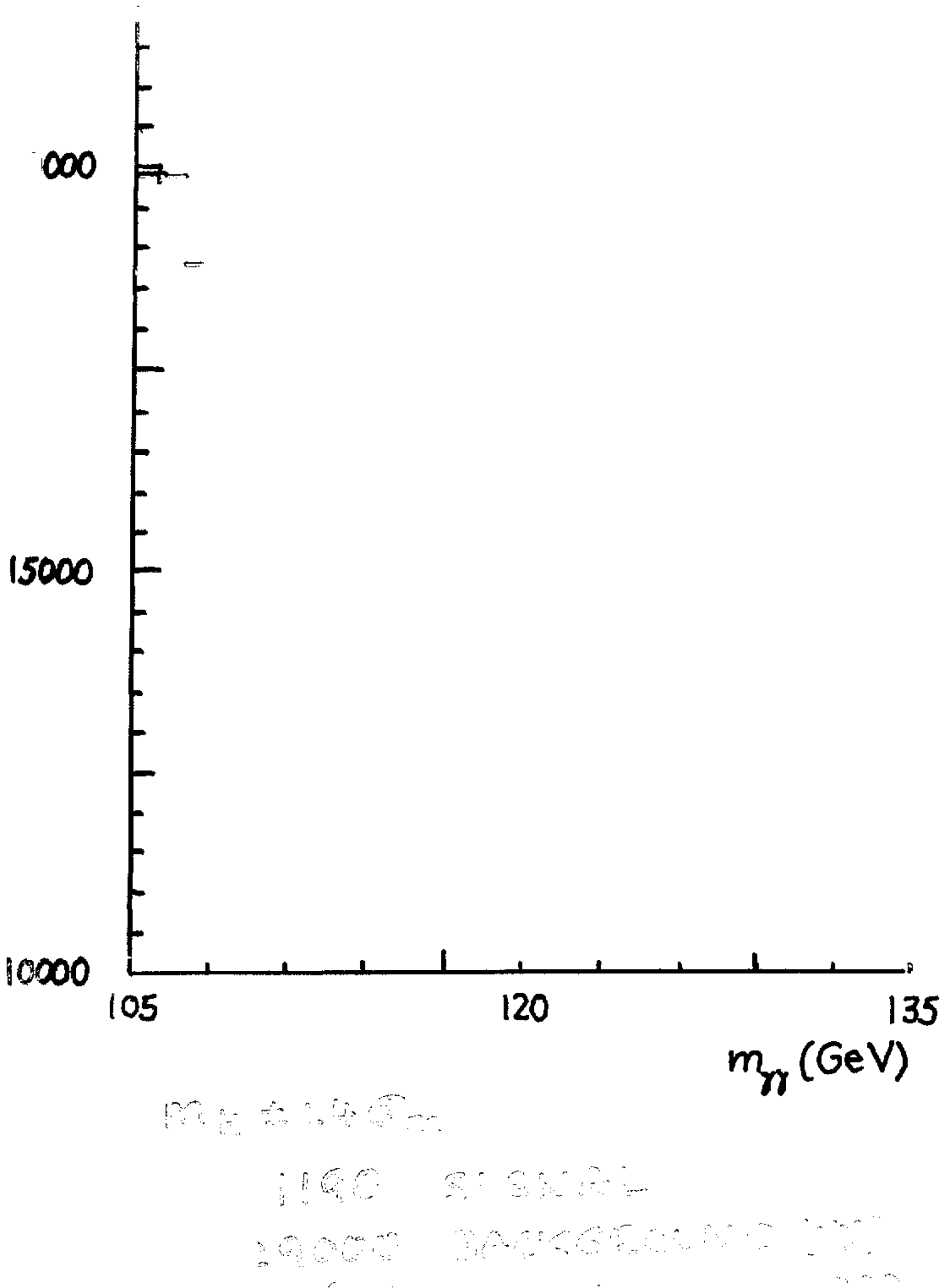
$\{$ PbWO4 ECAL (Tempe… Calibrat…

Main vertex reconstruction

$\sigma_M \sim 0.7$ GeV → 1.6 GeV (no vtx)




Events / 2 GeV
20000
17500
15000
12500
10000
105
120
135
$m_{\gamma\gamma}$ (GeV)

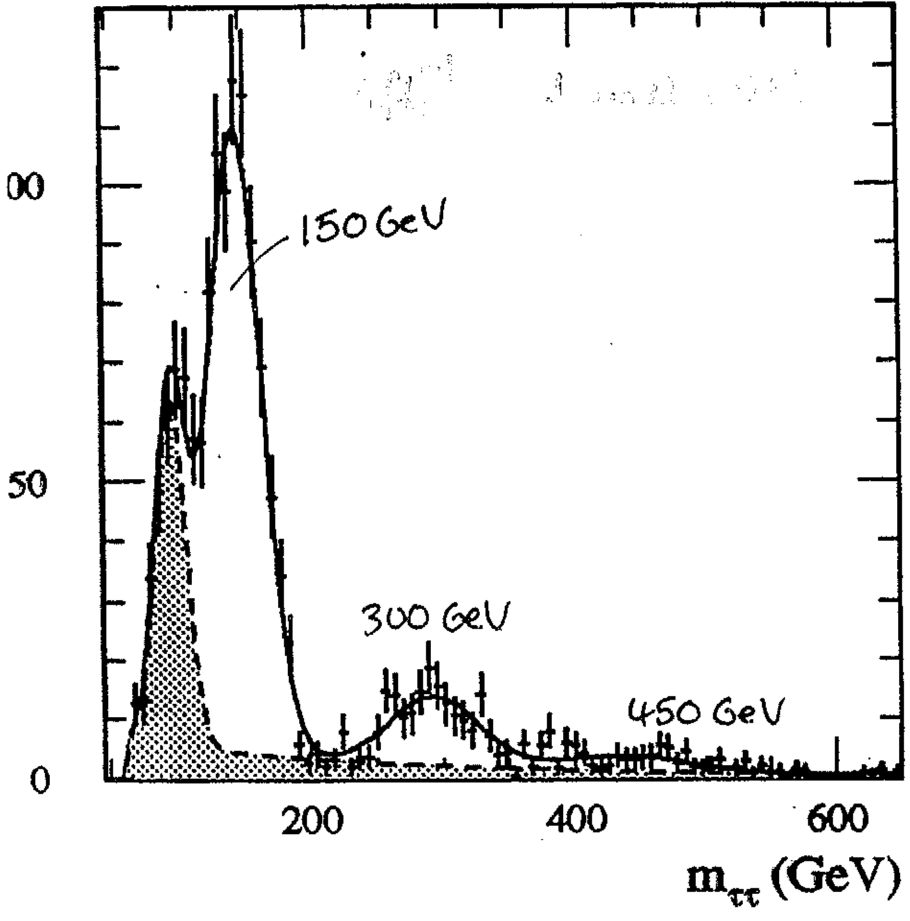

000
15000
10000
105
120
135
$m_{\gamma\gamma}$ (GeV)
1190 SIGNAL
19000 BACKGROUND

Associated Production

$b\bar{b}A,\ b\bar{b}H \rightarrow \underbrace{b\bar{b}}\tau^+\tau^-$

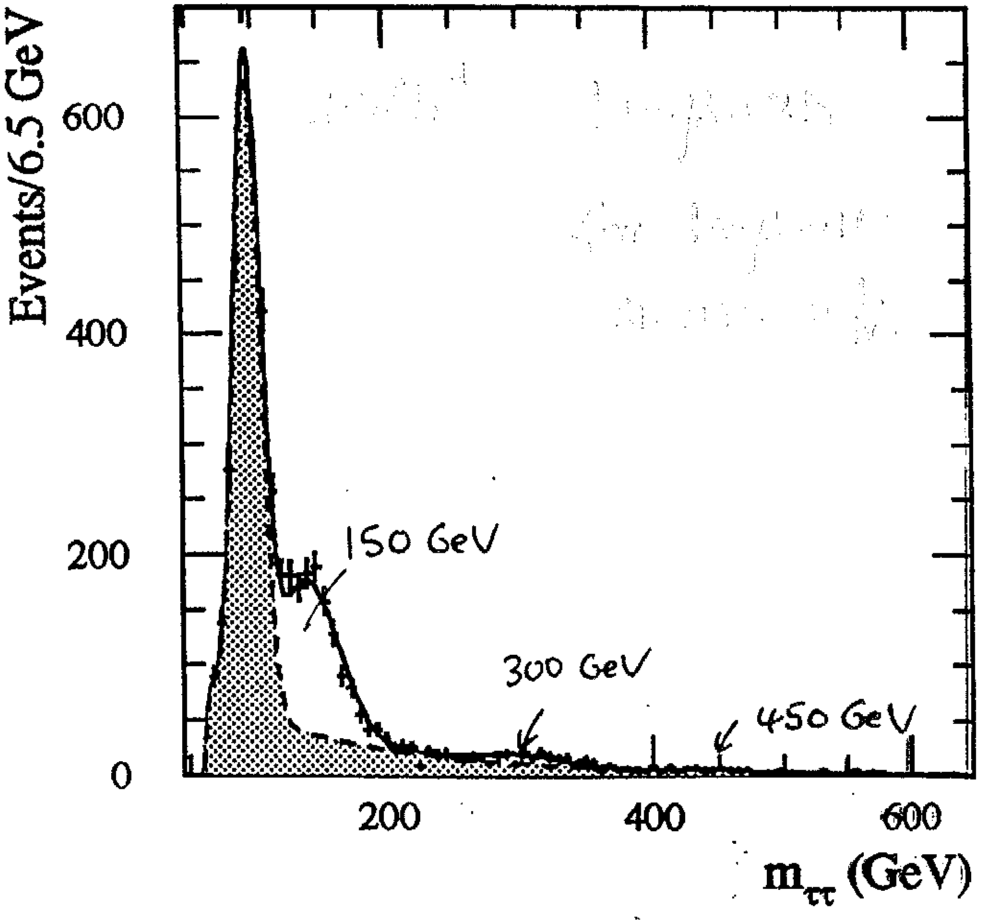
b-tag needs

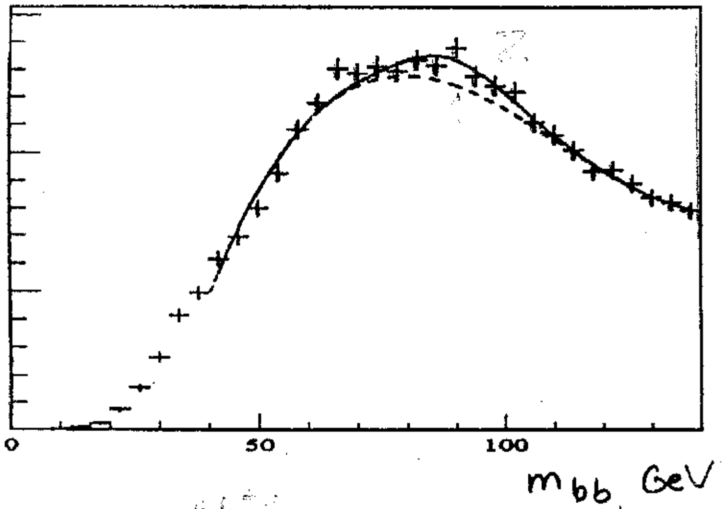
(2 layers pixel
4 layers Si-strip

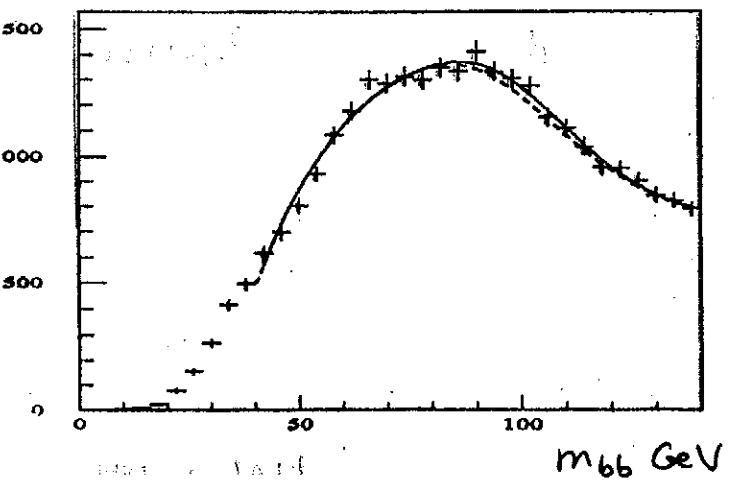


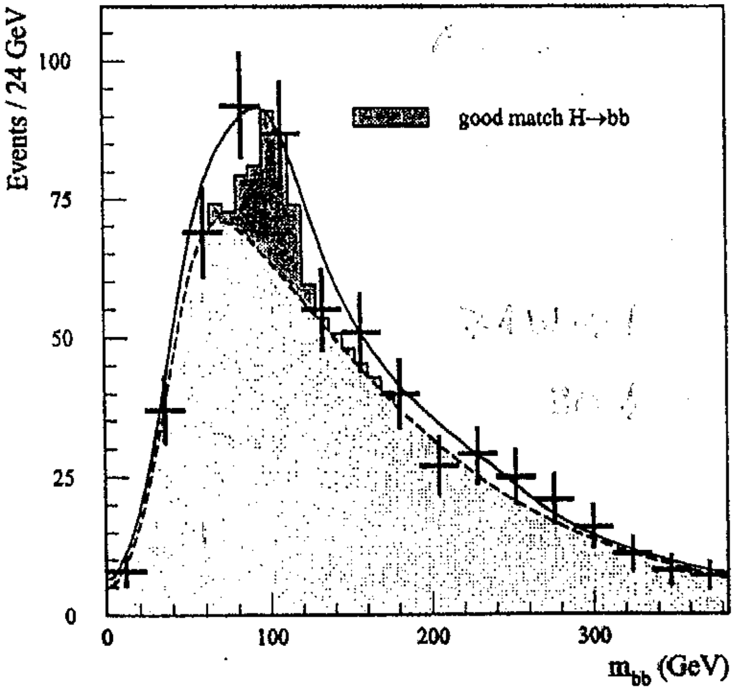
Direct Productio

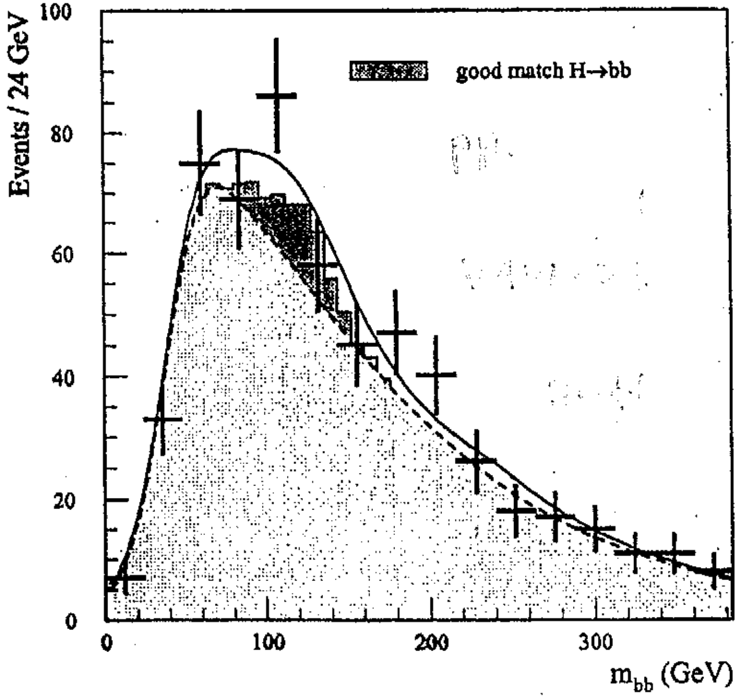
$gg \rightarrow A, H \rightarrow \tau^+\tau$




0
50
100
m_bb GeV


0
500
1000
1500
0
50
100
m_bb GeV

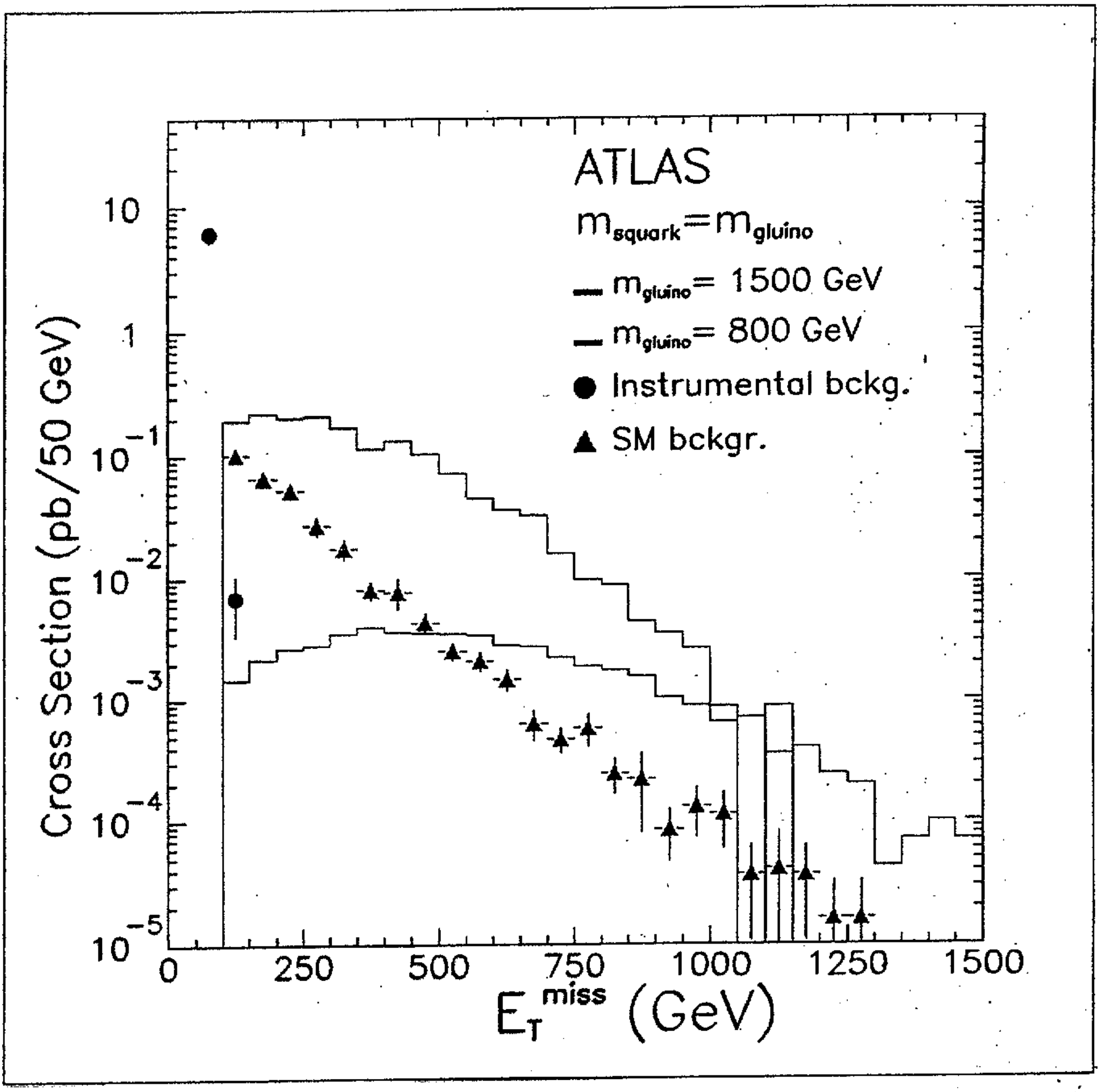

Events / 24 GeV
0
25
50
75
100
good match H→bb
0
100
200
300
m_bb (GeV)


Events / 24 GeV
0
20
40
60
80
100
good match H→bb
0
100
200
300
m_bb (GeV)

) LHC

SUPER SYMMETRY

GLUINO PRODUCTION



IF GAUGE UNIFICATION IS ASSUMED,

$$M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3$$

AT THE WEAK SCALE

$$m_{\tilde{\chi}_1^+} \leq M_2 = \frac{\alpha_2}{\alpha_3} M_3 = \frac{1}{3.5} m_{\tilde{g}}$$

[illegible]

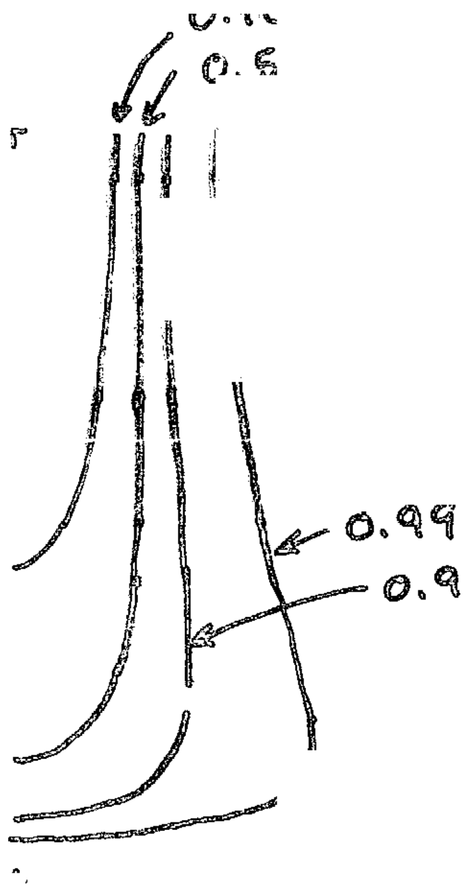
[illegible] GeV $\Longrightarrow m_{\tilde{g}} >$ [illegible]

(TEVATRON CAN REACH 300 GeV $\tilde{g}$)

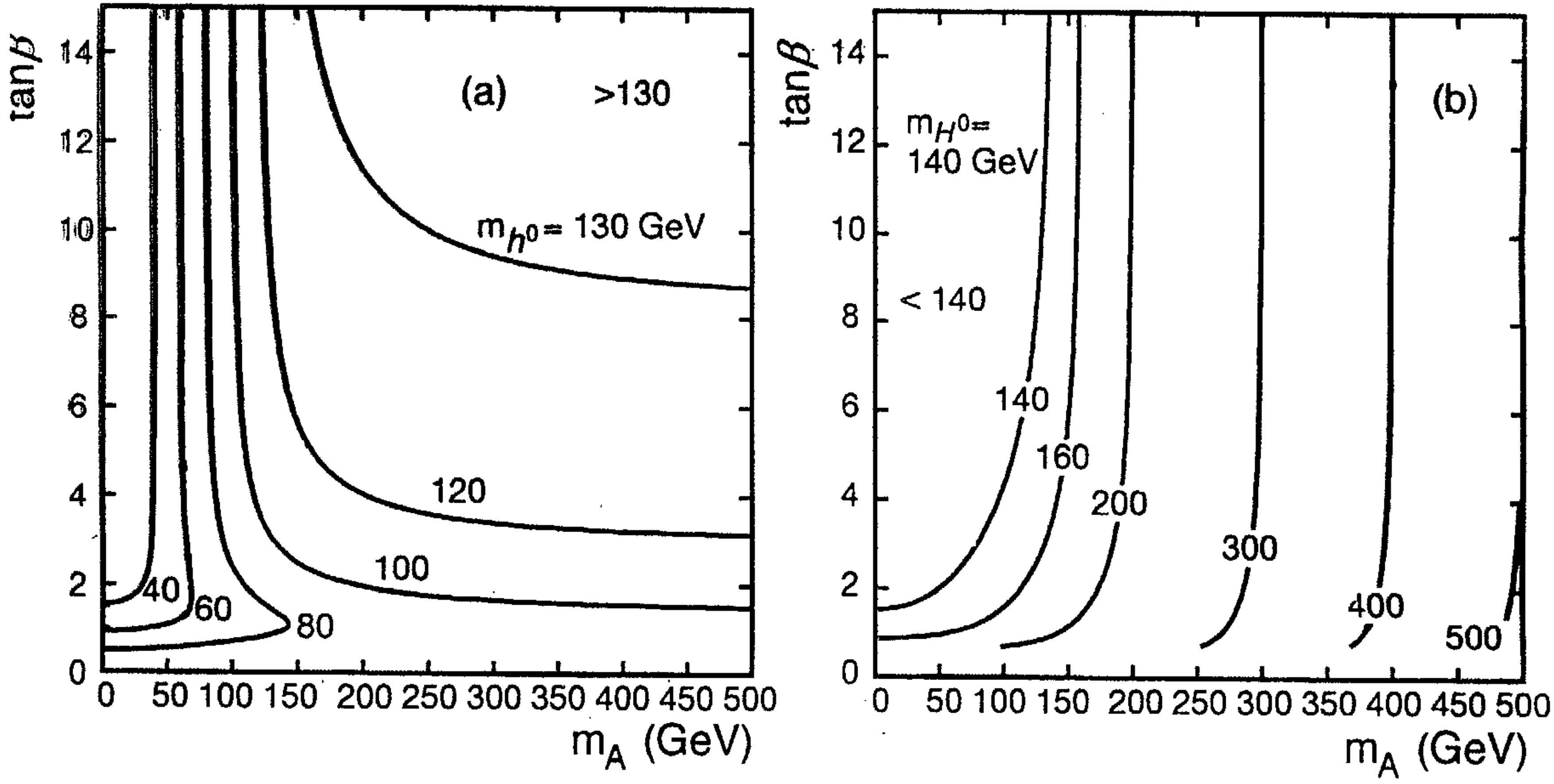
$\frac{300}{3.5} = 86$ GeV $\tilde{\chi}_1^+$: EXCLUDED @ LEP2

MASS DETERMINATION OF $\tilde{\chi}_1^0$, $\tilde{\chi}_1^+$ AT LC HELPS TO DETERMINE $m_{\tilde{g}}$, $m_{\tilde{q}}$ AND OTHER SUSY PARAMETERS AT LHC.

$\tilde{q}$ AND $\tilde{g}$ CASCADE DECAYS ARE NASTY "NATURE" IS DIFFERENT



R. Van Kooten
LCWS95


tanβ
0
2
4
6
8
10
12
14
0 50 100 150 200 250 300 350 400 450 500
m_A (GeV)
(a)
>130
m_{h^0}= 130 GeV
120
100
80
60
40
(b)
m_{H^0}=
140 GeV
< 140
140
160
200
300
400
500

HIGGS BOSONS @ LC

1) DISCOVERY OF h^0 EASY

(IF NOT @ LEP2, LHC, ...)

$\sigma(e^+e^- \to Z^* \to Z h^0) \sim 0.2$ pb $M_{h^0} = 120$ GeV

MSSM $\sqrt{s} = 300$ GeV

$\int \mathcal{L}\, dt = 5 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \Rightarrow 1000\ h^0 Z / 10^7 \mathrm{sec}$

- EVEN FOR NMSSM (Okada LCWS95)

$\sigma > 0.06$ pb $250 \lesssim \sqrt{s} \lesssim 300$ GeV

2) PRECISION MEASUREMENTS OF h^0 PROPERTIES

① CROSS SECTION

$$\sigma(hZ) = \sigma(H_{SM} Z) \sin^2(\beta-\alpha)$$

$$(m_h = m_{H_{SM}})$$

$$\text{IF } \sigma(hZ) < 0.95\, \sigma(H_{SM} Z)$$

$\uparrow$ NO b-TAG

RECOIL MASS $Z \to e^+e^-, \mu^+\mu^-$

$\Rightarrow e^+e^- \to hA$ IS OPEN

BUT $\sigma(hA) = \frac{1}{2} \sigma(\nu_\mu \bar{\nu}_\mu) \bar{\beta}^3 \cos^2(\beta-\alpha)$

② SPIN - PARITY

$$\frac{d\sigma}{d\cos\theta_b^*} \sim \sin^2\theta_b^*$$

③ DECAY BRANCHING FRACTIONS

$$\Gamma(h\to b\bar b) \propto m_b^2 \underbrace{\text{[illegible]}} \nearrow \left[\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\right.$$

$$\Gamma(h\to c\bar c) \propto m_c^2 \underbrace{\text{[illegible]}} \nearrow \left[\sin(\beta-\alpha) + \frac{1}{\tan\beta}\cos(\beta-\alpha)\right]^2$$

$\Gamma(h\to gg) \propto$ [illegible] (TOP QUARK LOOP DOMINANT)

SINCE m_c AMBIGUITY IS LARGE, $\Gamma(h\to gg)$ SHOULD ALSO BE MEASURED.

LCWS93 Hildreth, Barklow, Burke

$B(b\bar b)$, $B(c\bar c + gg)$, [illegible]

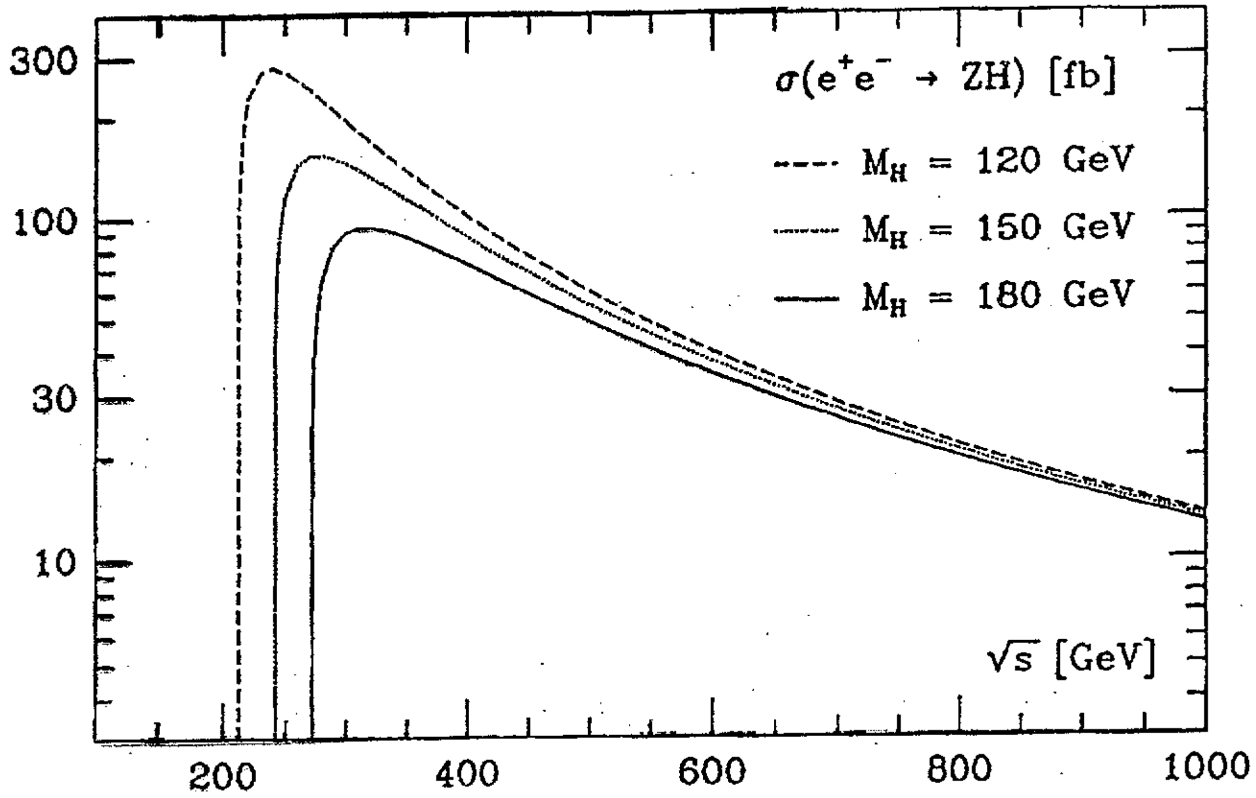
LCWS95 Nakamura, Kawagoe, Okada

$$\text{[illegible]} \propto \frac{1}{\text{[illegible]}} \simeq \left(\frac{M_A{}^2 - M_h^2}{M_A{}^2 + M_Z^2}\right)^2 \Rightarrow M_A$$

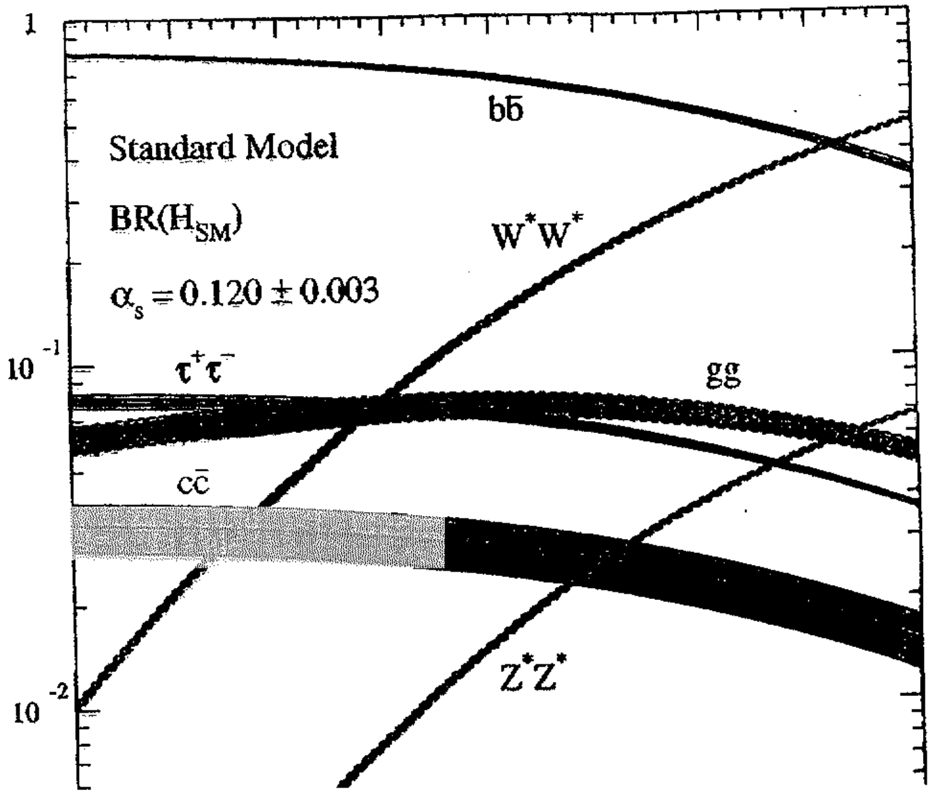
↖ LARGE $\tan\beta$

ECFA (Frascati, Oxford) Battaglia

[illegible] REALISTIC SIMULATION

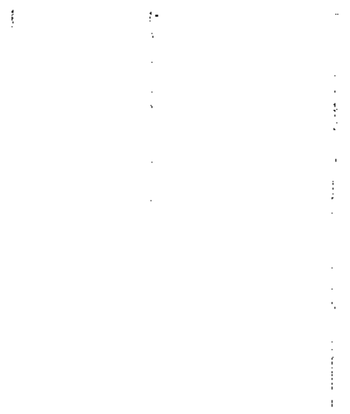


300
100
30
10
200
400
600
800
1000
σ(e⁺e⁻ → ZH) [fb]
M_H = 120 GeV
M_H = 150 GeV
M_H = 180 GeV
√s [GeV]

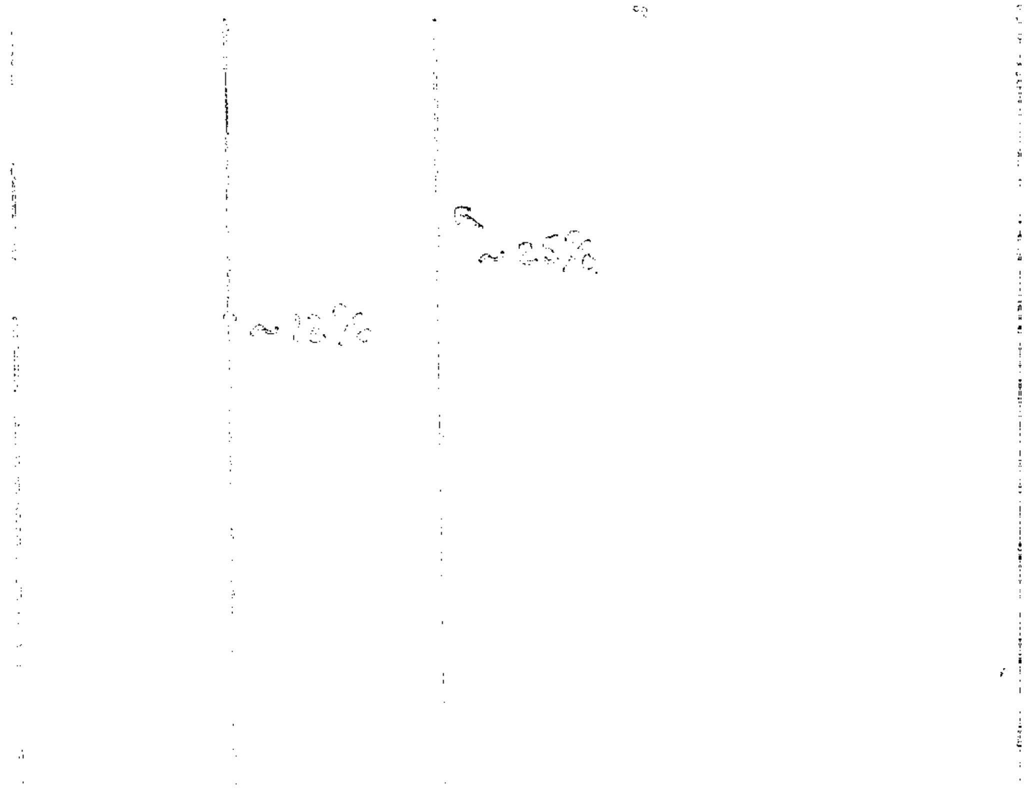


1
10⁻¹
10⁻²
b b̄
Standard Model
BR(H_SM)
α_s = 0.120 ± 0.003
W*W*
τ⁺τ⁻
gg
c c̄
Z*Z*

SM HIGGS CROSS SECTIO



SM HIGGS DECAY BRANCHING FRACTIONS



EXPERIMENTAL ISSUES

- m_c AMBIGUITY, SMALL $B(h \to c\bar{c})$

  $h \to gg$ SHOULD BE SEPARATED FROM $c\bar{c}$

  C-TAGGING

- $h \to WW^*$

  LARGE

  $B(h \to WW^*)$ ~ 13% $m_{H^0_{SM}}$ 120 GeV

  ~ 25%   130 GeV

  σ_{hZ} MEASUREMENT $\Rightarrow \sin^2(\beta-\alpha)$

$$\Rightarrow \quad \Gamma(h \to W^*W) = \Gamma(H_{SM} \to W^*W)\,\sin^2(\beta-\alpha)$$

$$\Rightarrow \quad \Gamma(h \to all) = \frac{\Gamma(h \to W^*W)}{B(h \to W^*W)}$$

$h \to W^*W$ MEASUREMENT

$$\Rightarrow \quad \Gamma(h \to b\bar{b}) = B(h \to bb)\,\Gamma(h \to all)$$

$$\Rightarrow \quad \frac{\Gamma(h \to b\bar{b})}{\Gamma(H_{SM} \to b\bar{b})} = \frac{\sin^2\alpha}{\sin^2\beta}$$

$\simeq 0.72$ $M_A = 500$ GeV

$\simeq 0.91$ $M_A = 700$ GeV

(F. Richard Oxford ECFA)

- FINALLY, SIMULTANEOUS FIT

  USING $B(h \to b\bar{b})$, $B(h \to gg)$, $B(h \to c\bar{c})$,
  $B(h \to \tau^+\tau^-)$, $B(h \to W^*W)$, $\sigma(hZ)$

SUPERSYMMETRY

SU(5)

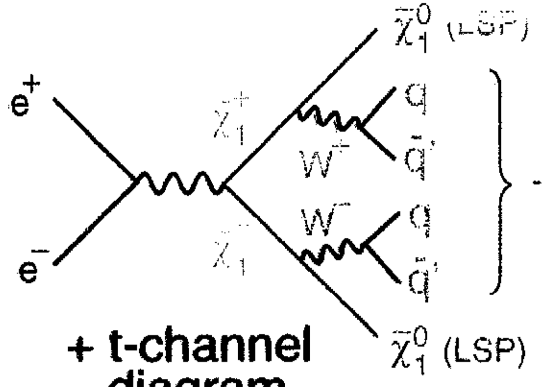
SUSY GUTs

α, $\sin^2\bar{\theta}_W$

$\Rightarrow \alpha_s = 0.120$

$\alpha_s^{exp} = 0.118$

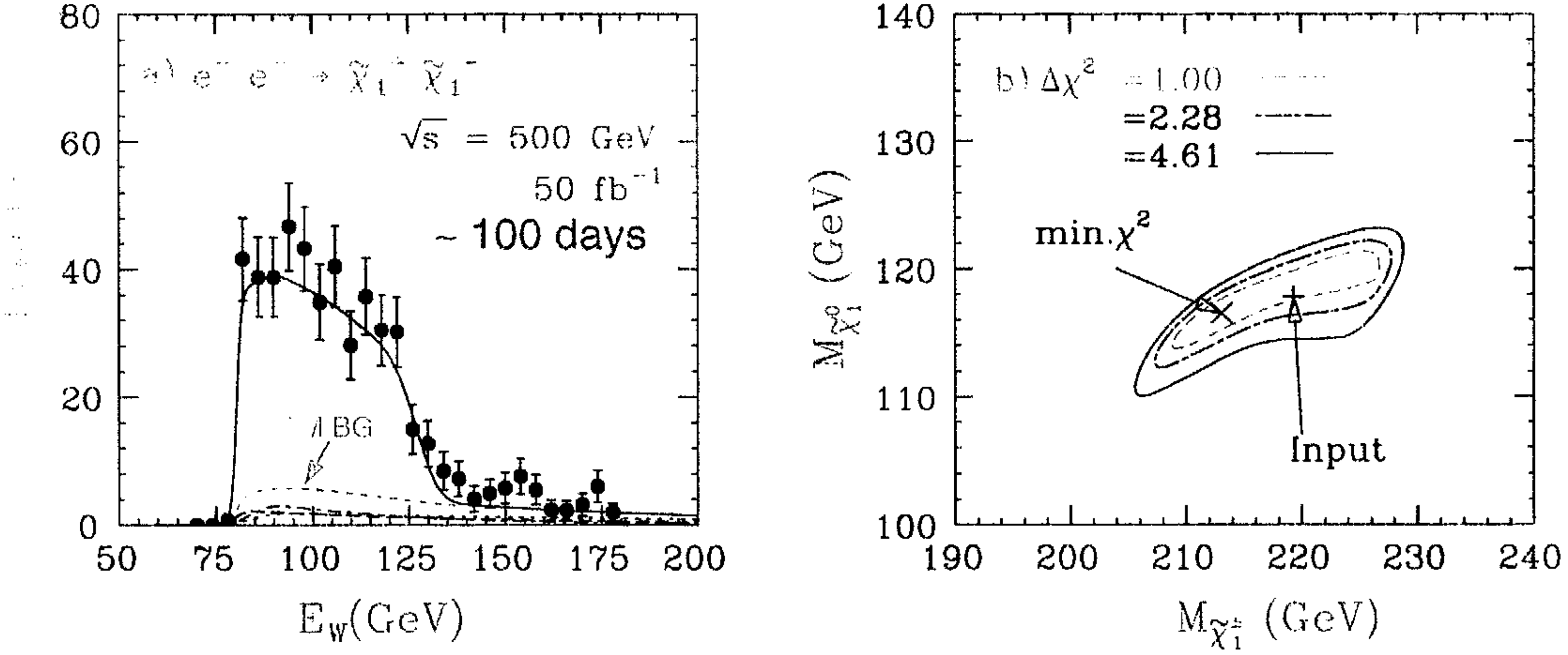
Mass Determination



+ t-channel diagram

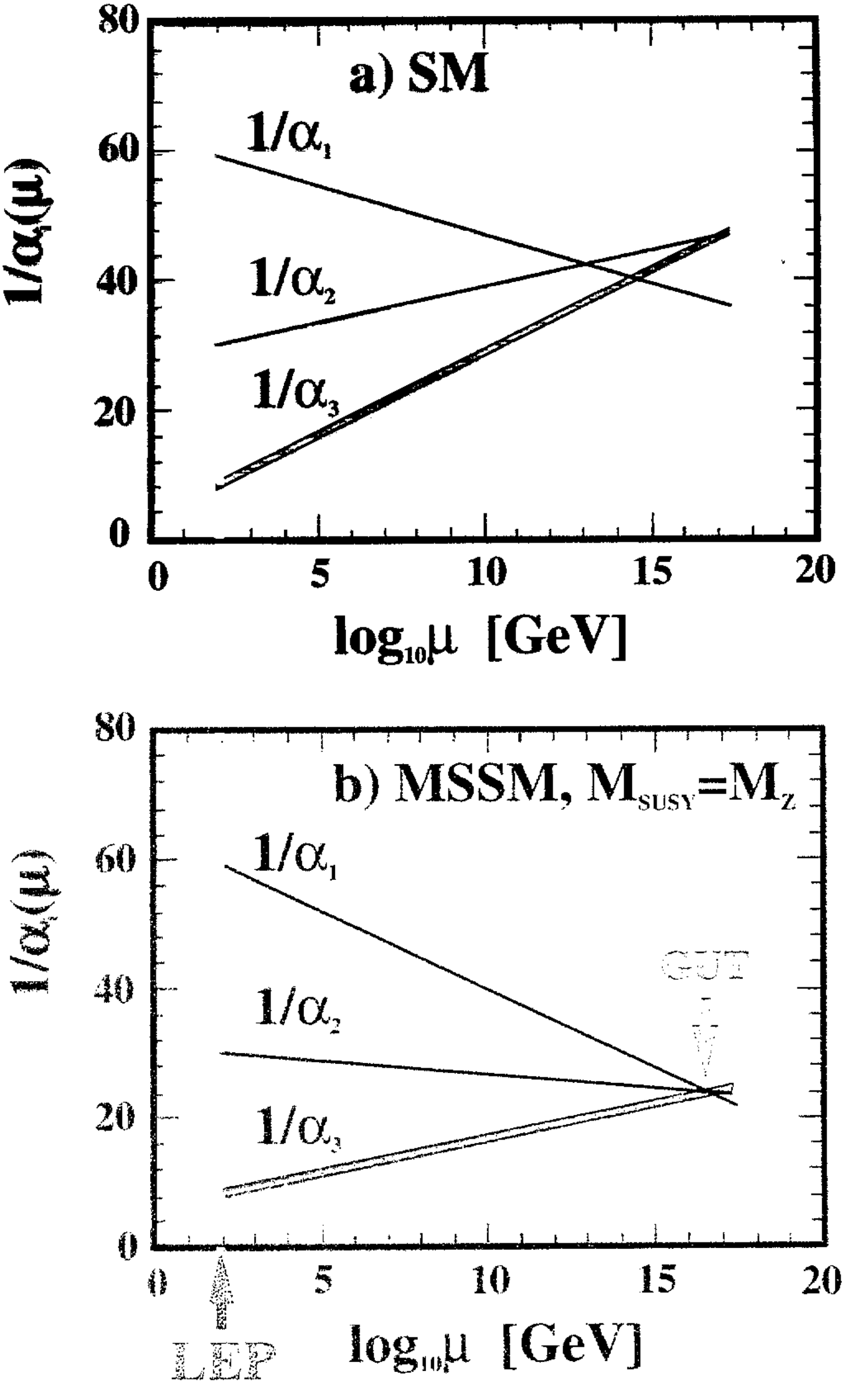
Measure E_W

End points



$\Delta m_{\tilde\chi_1^\pm} \approx 8$ GeV

$m_{\tilde\chi_1^0}$ from $\tilde l_R^\pm$ studies


a) SM
$1/\alpha_1$
$1/\alpha_2$
$1/\alpha_3$
$1/\alpha_i(\mu)$
80
60
40
20
0
0
5
10
15
20
$\log_{10}\mu$ [GeV]
b) MSSM, $M_{SUSY}=M_Z$
$1/\alpha_1$
$1/\alpha_2$
$1/\alpha_3$
GUT
$1/\alpha_i(\mu)$
80
60
40
20
0
0
5
10
15
20
LEP
$\log_{10}\mu$ [GeV]

ISSUES ON SUSY

1) WHERE ARE THEY ?

$m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^+}$, $m_{\tilde{\ell}_R}$, ...

2) SUSY BREAKING MECHANISM ?

SUPERGRAVITY

GAUGE MEDIATED SUSY BREAKING

3) UNIFICATION AT GUT SCALE ?

GAUGE UNIFICATION

$\alpha_1 : \alpha_2 : \alpha_3 = M_1 : M_2 : M_3$

YUKAWA UNIFICATION

DETECTOR

1) FORWARD COVERAGE

2) e^-- POLARIZATION

3) DECAY IN FLIGHT ⇐ GMSB

2NDARY VERTEX

LONG LIVED PARTICLES

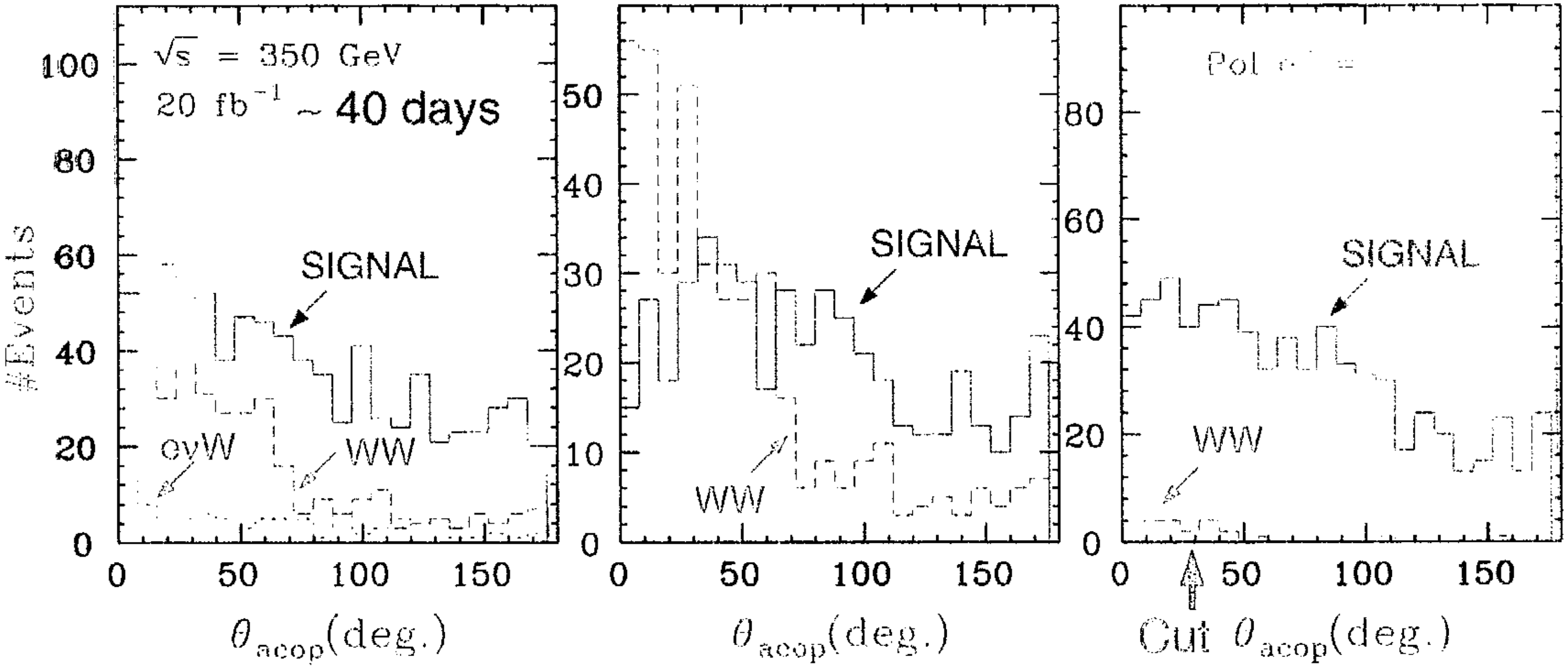
TOF dE/dX

K. Fujii et al.

Acoplanarity Distributions

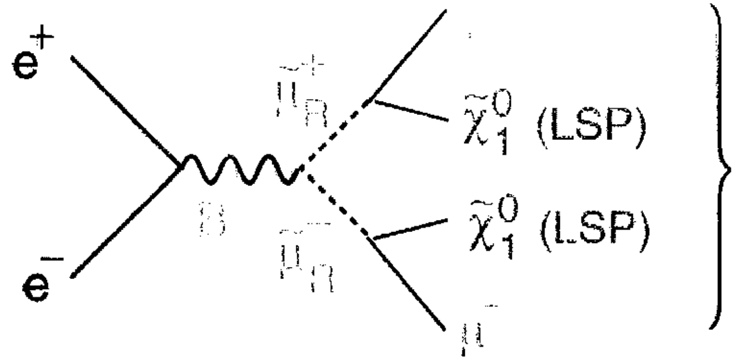
$e^+e^- \to \tilde{e}^+_R\tilde{e}^-_R$ Pol $e^- = 0$

$e^+e^- \to \tilde{\mu}^+_R\tilde{\mu}^-_R$ Pol $e^- = 0$ Pol $e^- = +0.$ $= e^-_R$



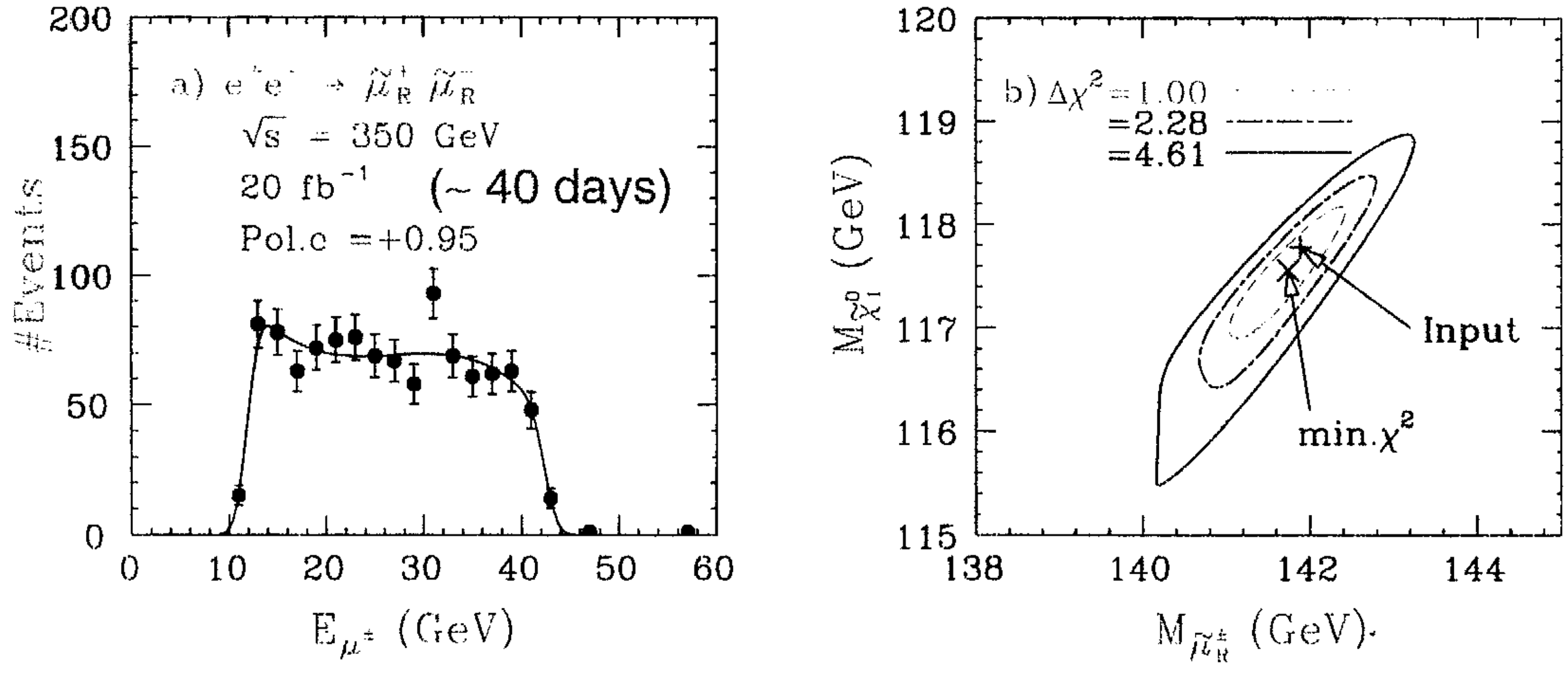
-------------→ Very Clean Sample for Precision Studies!

Mass Dete

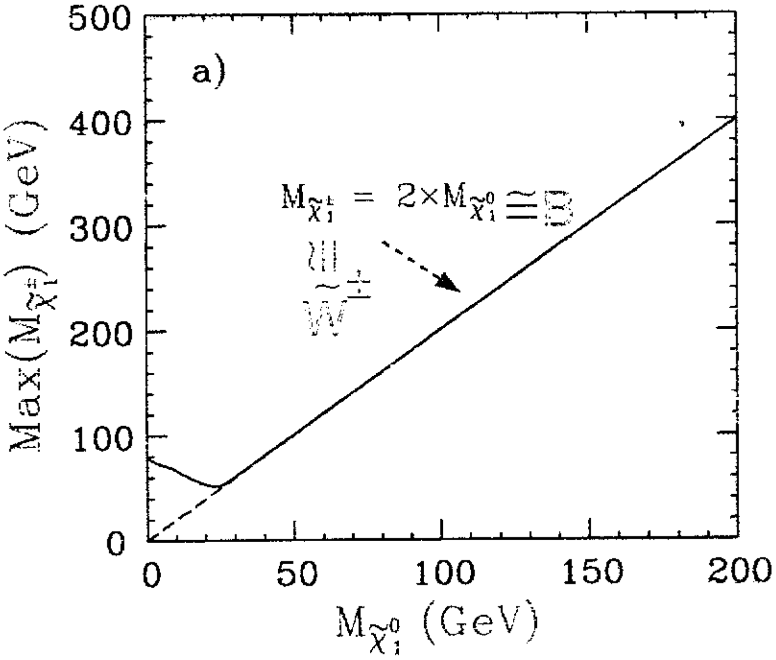


Measure E_μ

End points

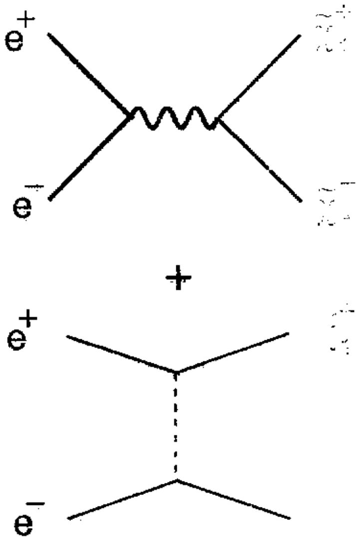


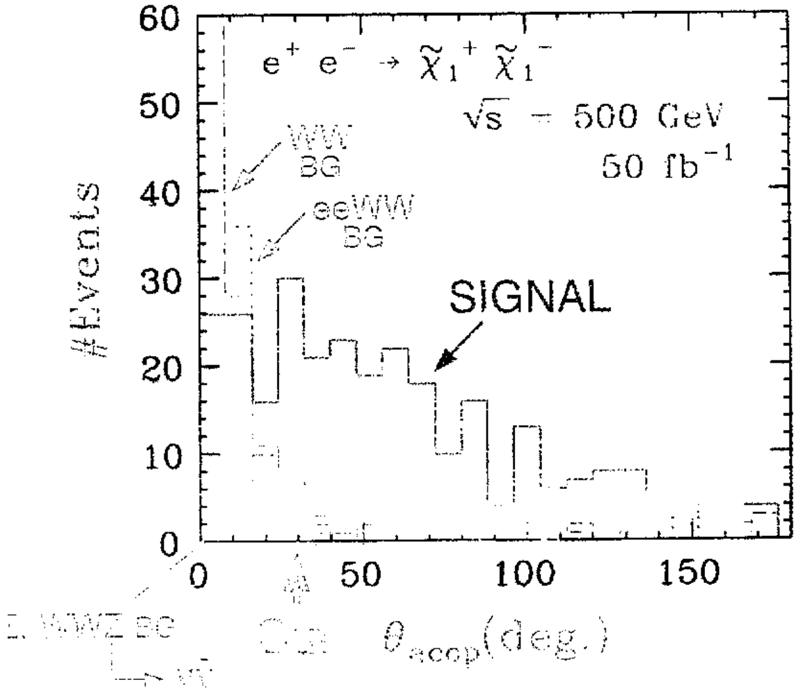
($\tilde{l}_R^\pm$ Studies) → Upper limits on



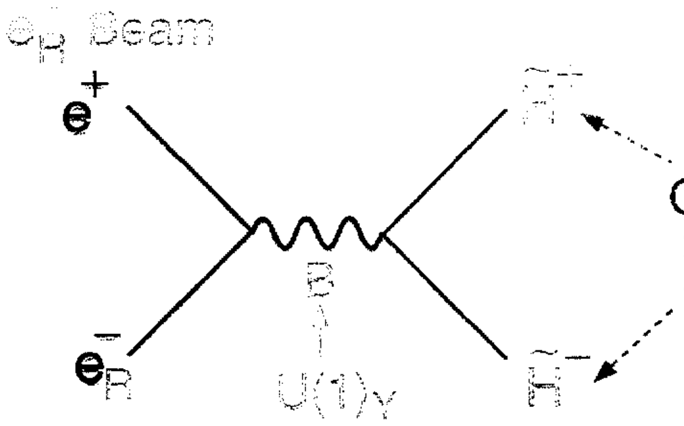
--→ Set $\sqrt{s}$ just above 4× m_{LSP}, look for $\tilde{\chi}_1^\pm$

$\tilde{\chi}_1^\pm$ --→ Signal = Acoplanar W^+W^- → $q\bar{q}'$ → $q\bar{q}'$ 4 Jet





$\sigma_{\tilde{\chi}_1^+\tilde{\chi}_1^-}$ Measurement



Only $\tilde{H}^\pm$ components in $\tilde{\chi}_1^\pm$ contribute !

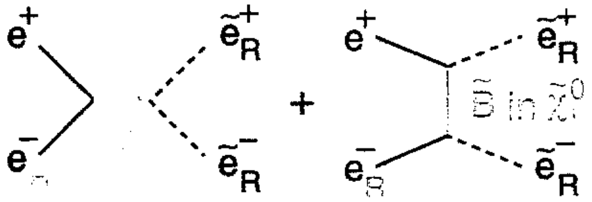
cf.) $e^+e^- \to W^+W^-$

$$\tilde{\chi}_1^\pm = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$$

$$\bullet = \langle \tilde{H}^\pm | \tilde{\chi}_1^\pm \rangle$$

--------► We can determine the composition of $\tilde{\chi}_1^\pm$!

Global Fit



We know

$m_{\tilde{\chi}_1^0}$ (= LSP) $\quad m_{\tilde{\chi}_1^\pm} \quad \sigma(e^+e_R^- \to \tilde{e}_R^+\tilde{e}_R^-) \quad \sigma(e^+e_R^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$

Mass Matrices $\quad \langle \tilde{H}^\pm | \tilde{\chi}_1^\pm \rangle$

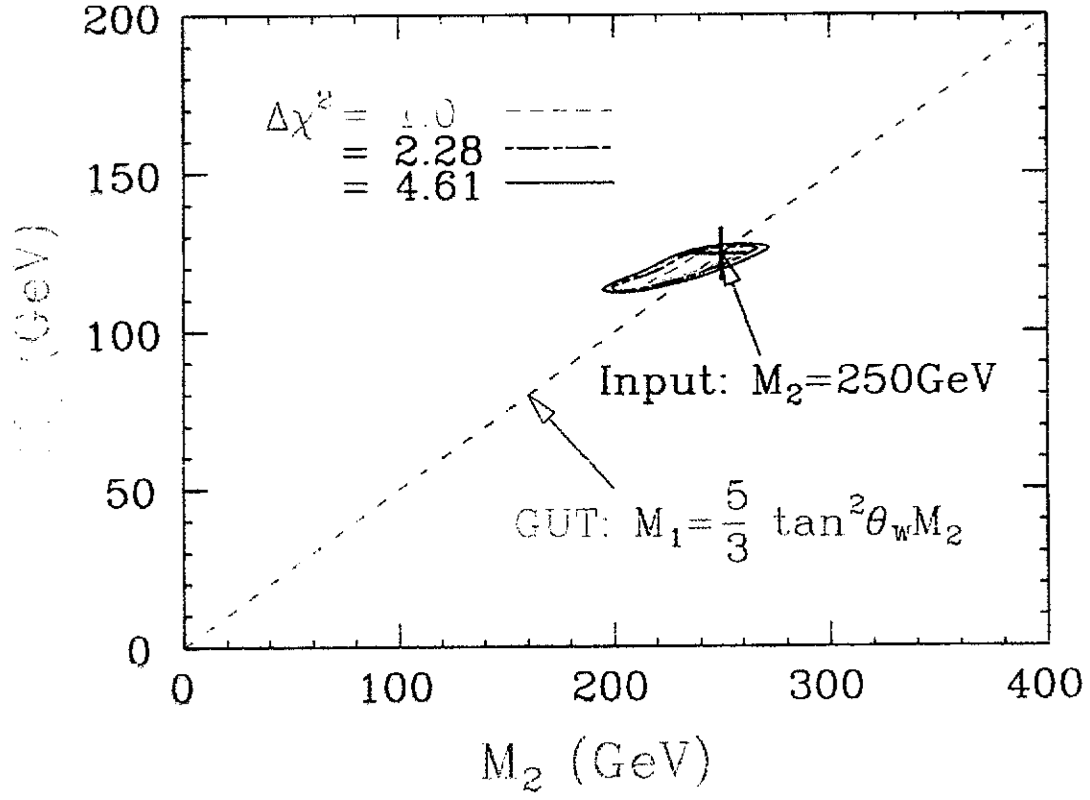
Forget the GUT relation and test if the GUT relation

st of GUT Relati

Common Gaugino Mass at the GUT scale

$$\text{GUT} \dashrightarrow \frac{\qquad}{\quad} = \frac{M}{\alpha_{GUT}}$$

$$i = \begin{cases} 1 \; U(1)_Y \\ 2 \; SU(2)_L \\ 3 \; SU(3)_C \end{cases}$$



If things turn out this way, we will be forced to believe GUT !

$\tilde{\tau}^-$ (SCALAR TAU) $m_{\tilde{e}_L, \tilde{\mu}_L}$ —

$$\tilde{\tau}_1 = \tilde{\tau}_L \cos\theta_{\tilde{\tau}} + \tilde{\tau}_R \sin\theta_{\tilde{\tau}}$$

$m_{\tilde{e}_R, \tilde{\mu}_R}$ —

1) REMOVE $W^+W^- \rightarrow \tau\nu\tau\nu$ BY e^- BEAM POLARIZATION

2) REMOVE $e^+e^- \tau^+\tau^-$ BY ACOPLANARITY ANGLE CUT.

$E^{VIS}_{\tau\text{-JET}}$ SPECTRUM $\Rightarrow$

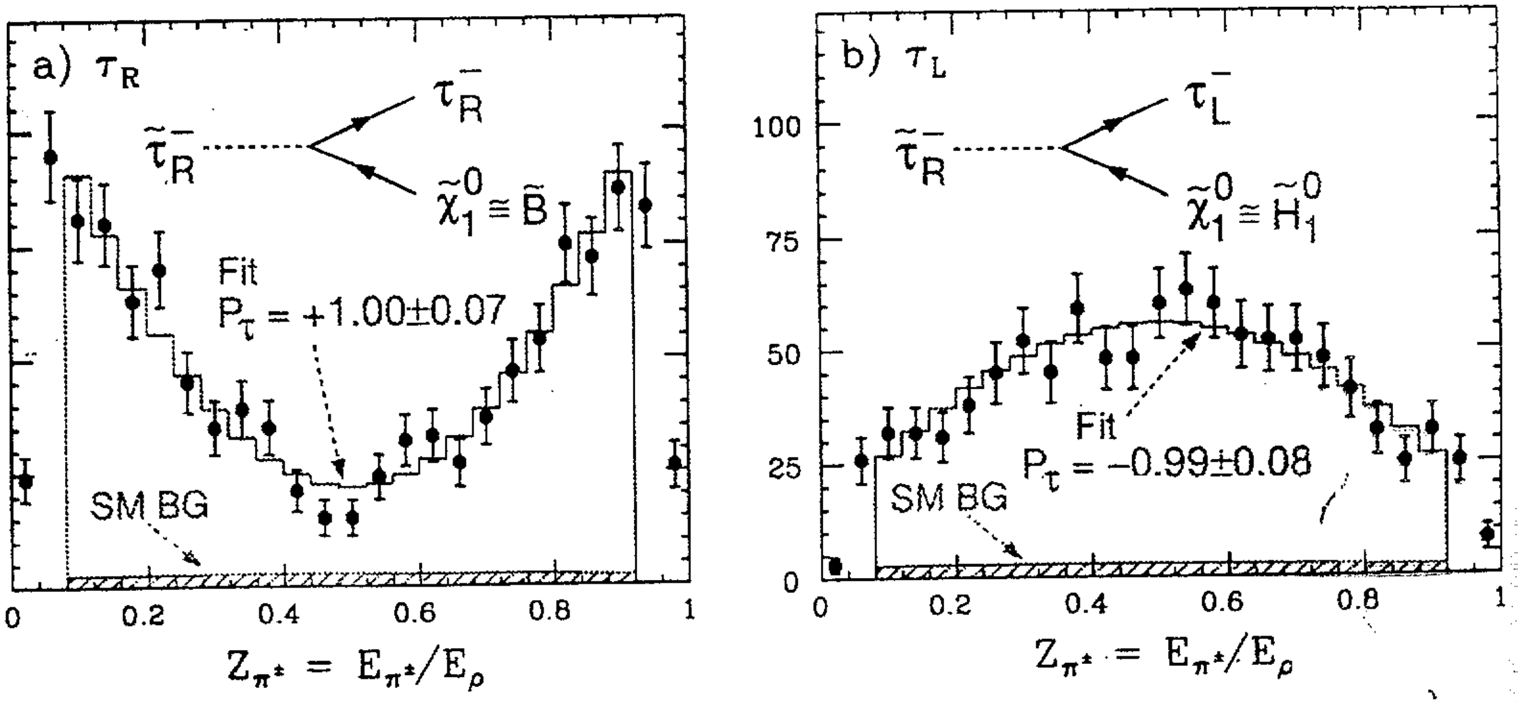
$\sigma_{\tilde{\tau}_1 \tilde{\tau}_1}$ MEASUREMENT $\Rightarrow$

$m_{\tilde{\chi}^0_1}$, $m_{\tilde{\chi}^+_1}$ (OR CUT)

$\tilde{\tau}_1 \rightarrow \tau \, \tilde{\chi}^0_1$ (τ POLARIZATION)

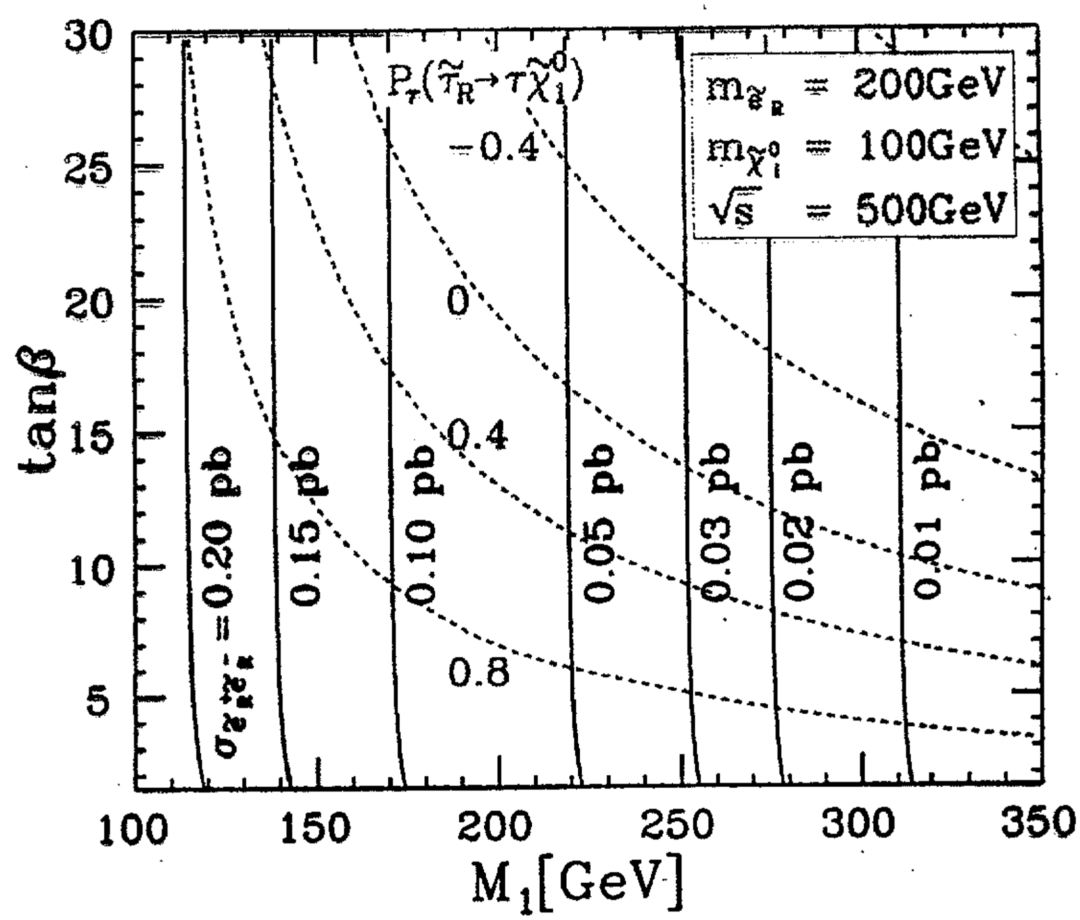
$\sigma_{\tilde{e}^+_R \tilde{e}^-_R}$

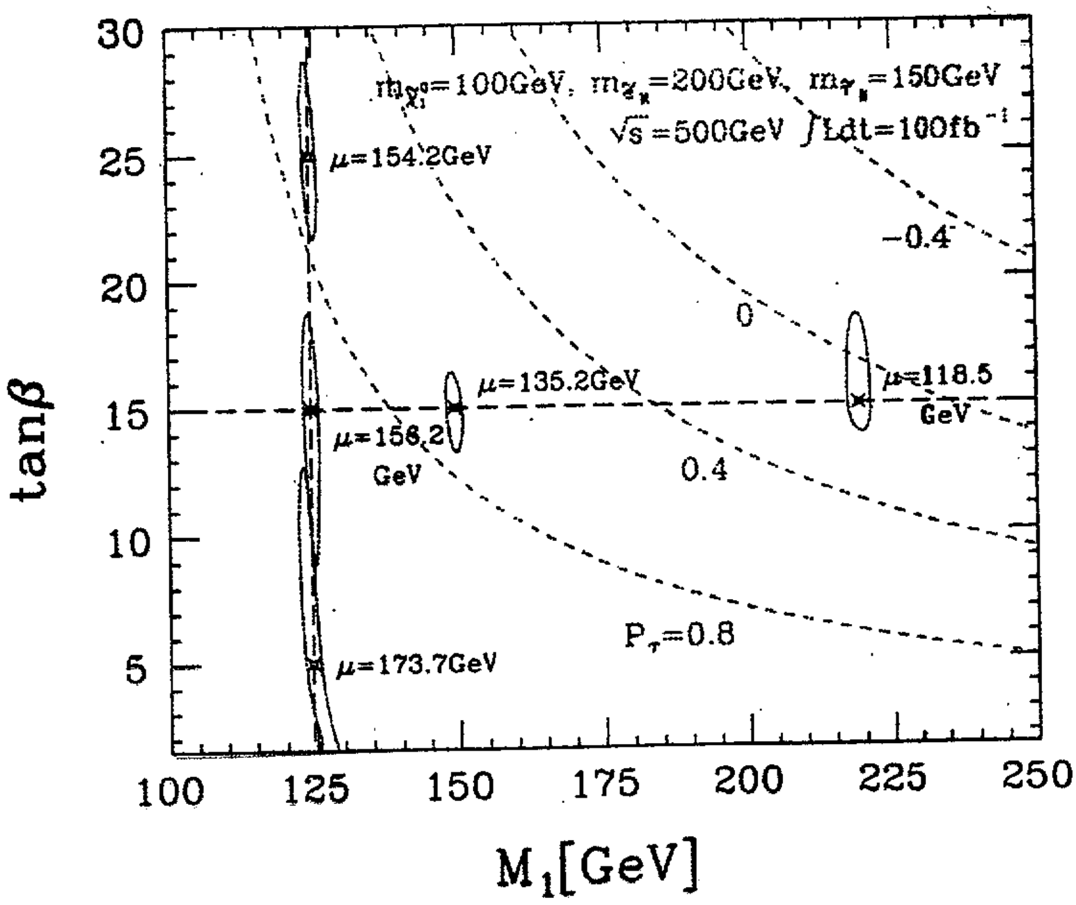
↗ ↙


a) τ_R
$\tilde{\tau}_R^-$
τ_R^-
$\tilde{\chi}_1^0 \cong \tilde{B}$
Fit
$P_\tau = +1.00\pm0.07$
SM BG
0
0.2
0.4
0.6
0.8
1
$Z_{\pi^\pm} = E_{\pi^\pm}/E_\rho$
b) τ_L
$\tilde{\tau}_R^-$
τ_L^-
$\tilde{\chi}_1^0 \cong \tilde{H}_1^0$
Fit
$P_\tau = -0.99\pm0.08$
SM BG
100
75
50
25
0
0
0.2
0.4
0.6
0.8
1
$Z_{\pi^\pm} = E_{\pi^\pm}/E_\rho$

$\sigma_{\tilde{e}_R^+ \tilde{e}_R^-}$, $P_\tau(\tilde{\tau}_R \to \tau \tilde{\chi}_1^0)$

$\Rightarrow +$


$P_\tau(\tilde{\tau}_R \to \tau\tilde{\chi}_1^0)$
$m_{\tilde{e}_R}$ = 200GeV
$m_{\tilde{\chi}_1^0}$ = 100GeV
$\sqrt{s}$ = 500GeV
−0.4
0
0.4
0.8
$\sigma_{\tilde{e}_R^+\tilde{e}_R^-}$ = 0.20 pb
0.15 pb
0.10 pb
0.05 pb
0.03 pb
0.02 pb
0.01 pb
tanβ
30
25
20
15
10
5
100
150
200
250
300
350
M_1[GeV]


$m_{\tilde{\chi}_1^0}$=100GeV, $m_{\tilde{e}_R}$=200GeV, $m_{\tilde{\tau}_R}$=150GeV
$\sqrt{s}$=500GeV ∫Ldt=100fb^{-1}
μ=154.2GeV
μ=135.2GeV
μ=118.5 GeV
μ=156.2 GeV
μ=173.7GeV
−0.4
0
0.4
P_τ=0.8
tanβ
30
25
20
15
10
5
100
125
150
175
200
225
250
M_1[GeV]

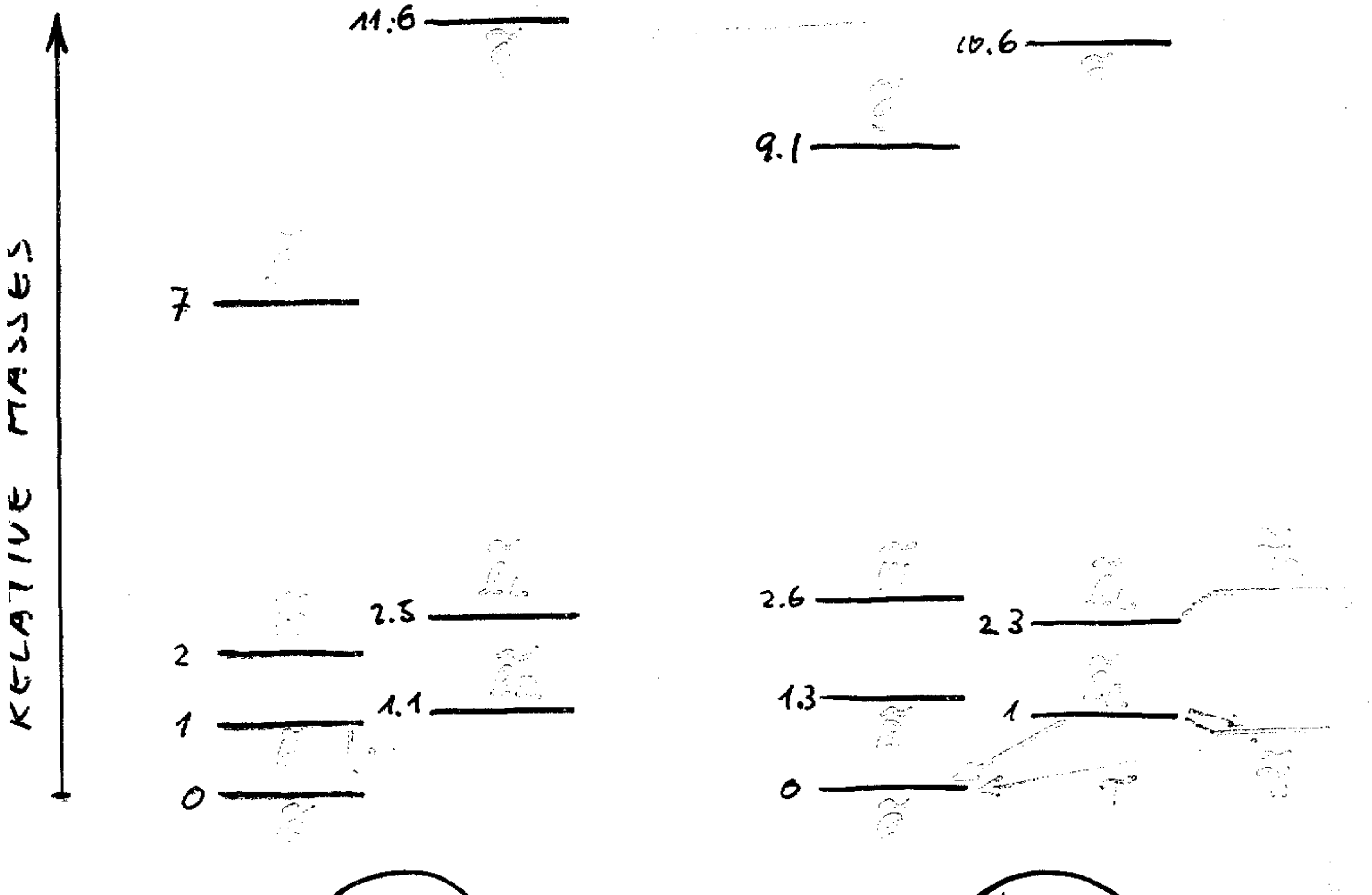
GAUGE MEDIATED SUSY BREAKING

LIGHTEST SUSY PARTICLE (LSP)
IS GRAVITINO ($\tilde{G}$, SPIN 3/2)

$$m_{\tilde{G}} = \frac{F}{\sqrt{3}M_{Pl}} \simeq 2.5\left[\frac{F}{(100\,\mathrm{TeV})^2}\right]\mathrm{eV} \quad \approx 0$$

- FCNC IS NATURALLY SUPPRESSED.
- SMALL NUMBER OF PARAMETERS

⇒ MASS SPECTRUM OF THE SIMPLEST MODEL



N=1 N=2

N=1 NLSP = $\tilde{\chi}^0_1$ $(\tilde{B})$

$$c\tau(\tilde{B} \to \tilde{G}\gamma) = 130\left(\frac{100\,\mathrm{GeV}}{m_{\tilde{B}}}\right)^5\left(\frac{\sqrt{F}}{100\,\mathrm{TeV}}\right)^4 \mu\mathrm{m}$$

) $e^+e^- \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1 \quad \tilde{\chi}^0_1 \rightarrow \gamma \tilde{G},\ Z\tilde{G},\ f\bar{f}\tilde{G}$

FULL SIMULATION

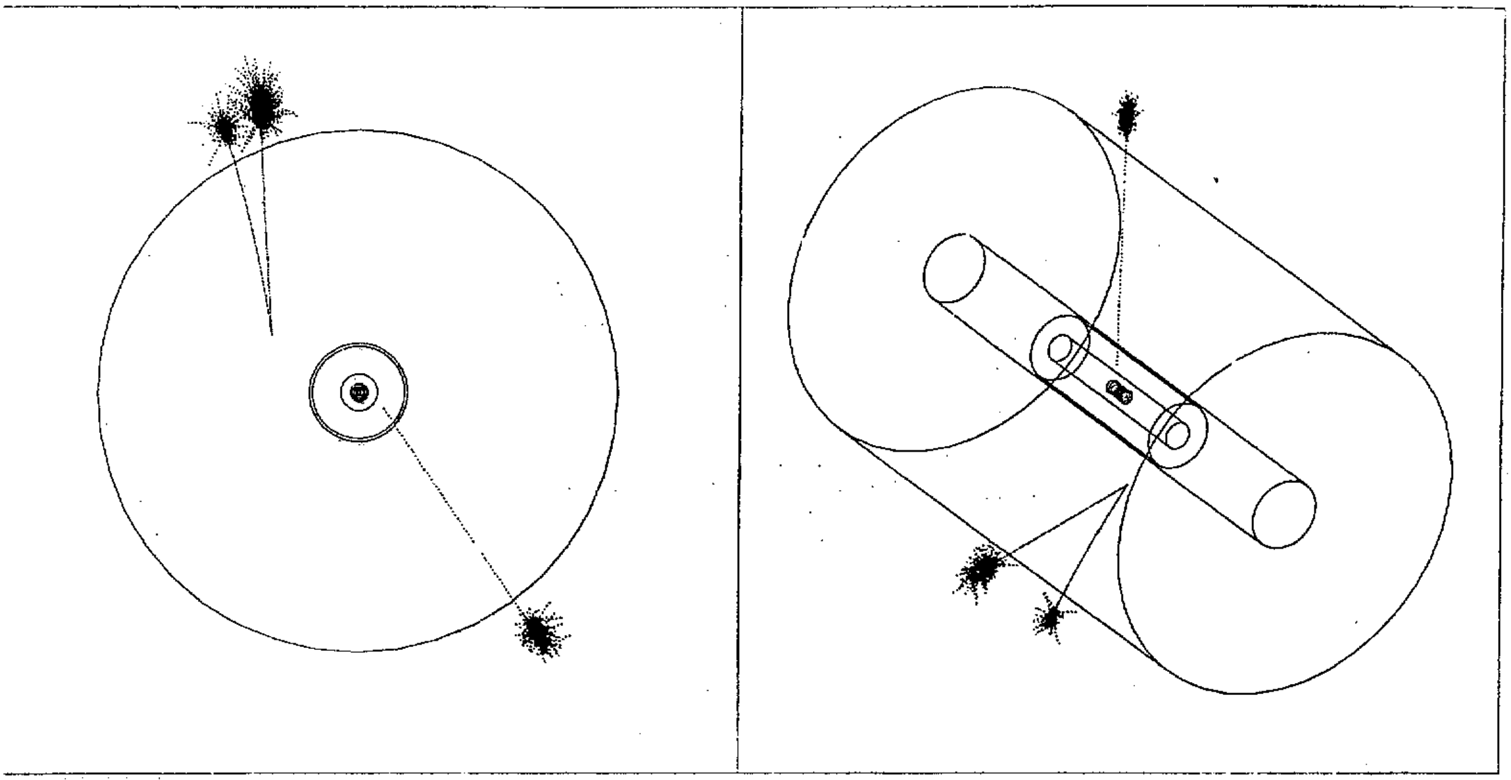
A. Blair (Oxford Meeting)

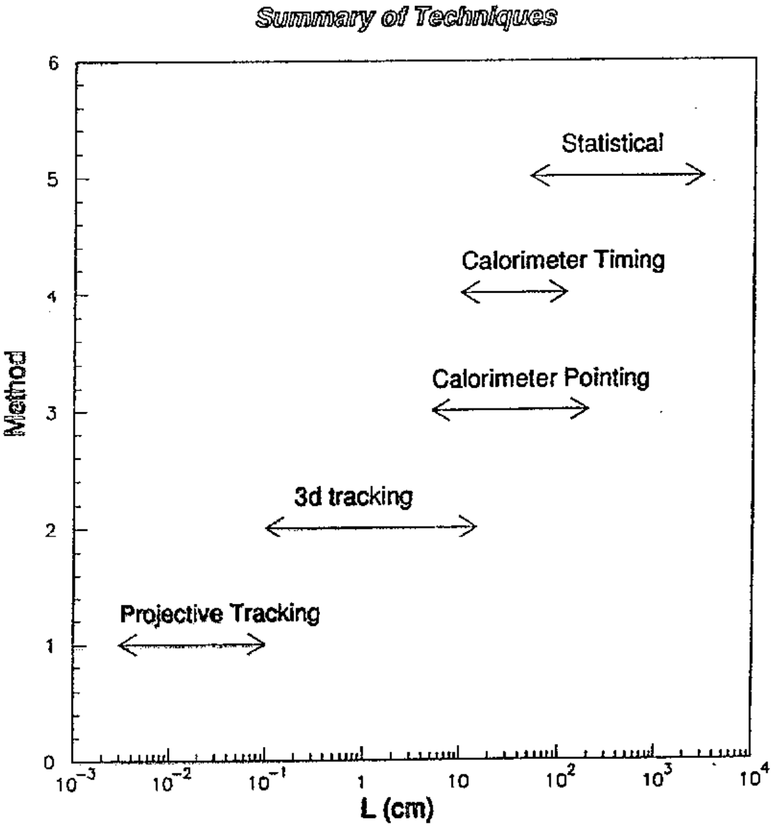
DIFFERENT TECHNIQUES FOR DIFFERENT CT

⇒ CORRESPONDS TO

⇒ DETECTOR REQUIREMENTS

2) $N=2$ $\tilde{\tau}$ NLSP




Summary of Techniques
Statistical
Calorimeter Timing
Calorimeter Pointing
3d tracking
Projective Tracking
Method
0
1
2
3
4
5
6
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
L (cm)

TOP QUARK THRESHOLD

$t\bar{t}$ CROSS SECTION
NEAR THE THRESHOLD
DEPENDS ON

$\sqrt{s}$, m_t, Γ_t, α_s, m_H, [illegible]

$$\sigma_{t\bar{t}} \Rightarrow |\psi(\vec{x}=0)|^2$$

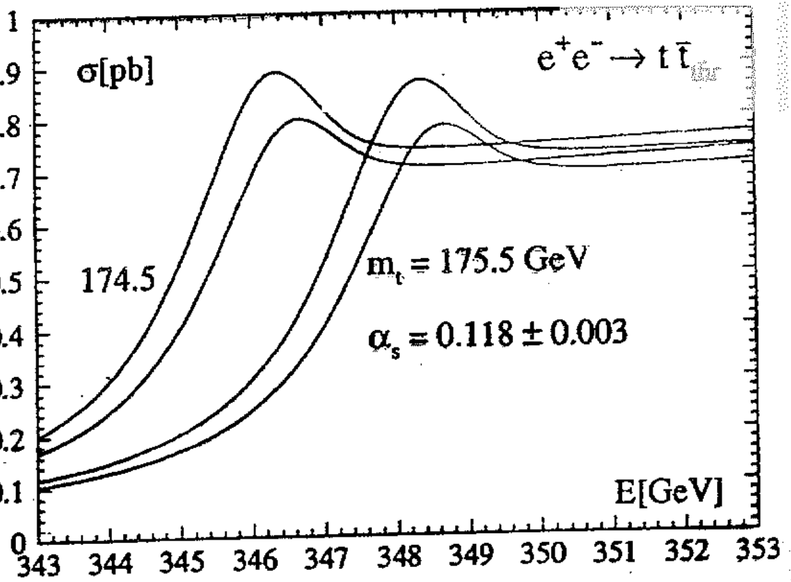
$$\frac{d\sigma}{dP_t} \Rightarrow |\tilde{\psi}(\vec{p})|^2$$

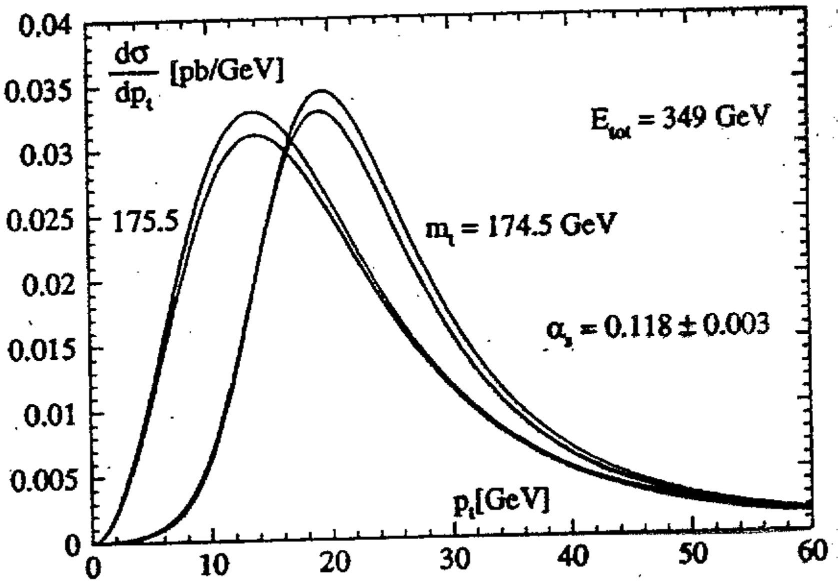
$$\Delta m_t \simeq 120\,\text{MeV}$$

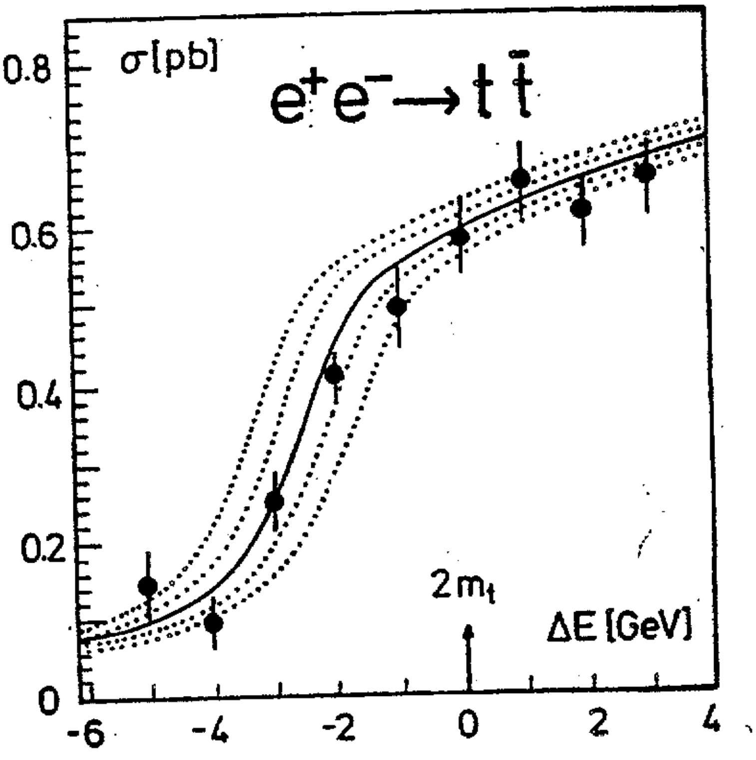
$$\Delta\alpha_s \simeq 0.003$$

WITH 50 fb^{-1}

DESY / ECFA


σ[pb]
e⁺e⁻ → t t̄_thr
174.5
m_t = 175.5 GeV
α_s = 0.118 ± 0.003
E[GeV]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
343
344
345
346
347
348
349
350
351
352
353

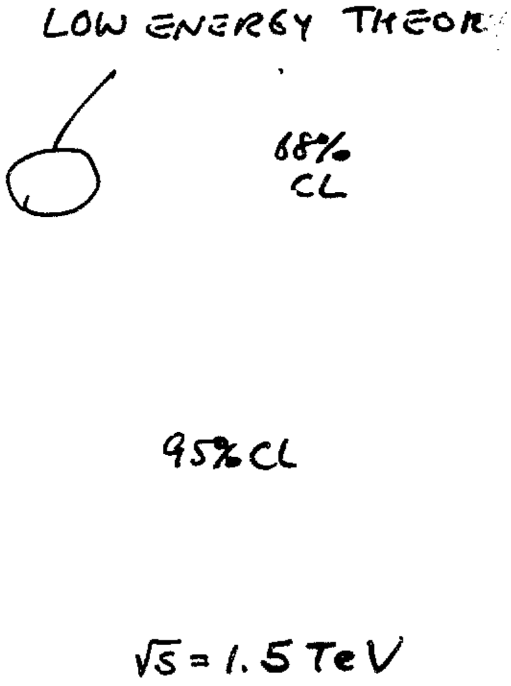

dσ/dp_t [pb/GeV]
E_tot = 349 GeV
175.5
m_t = 174.5 GeV
α_s = 0.118 ± 0.003
p_t[GeV]
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0
10
20
30
40
50
60


σ[pb]
e⁺e⁻ → t t̄
2m_t
ΔE [GeV]
0
0.2
0.4
0.6
0.8
-6
-4
-2
0
2
4

STRONG WW SCATT.

T. Barklow et al.

ex. TECHNIPION FORMFACTOR F_T



BEAM POLARIZATION

$\Rightarrow \mathrm{Im}(F_T)$

LET = low energy theory

$(M_{\rho_T} \to \infty)$

$\sqrt{s} = 500$ GeV

$M_{\rho_T} \approx 2.5$ TeV

CAN BE EXCLUDED

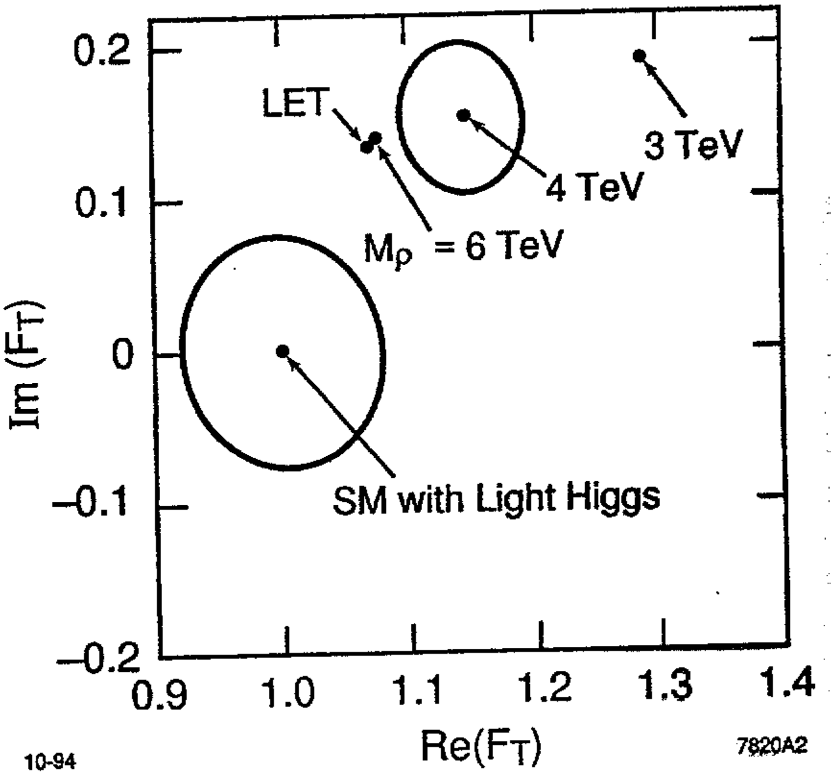
$\sqrt{s} = 1.5$ TeV

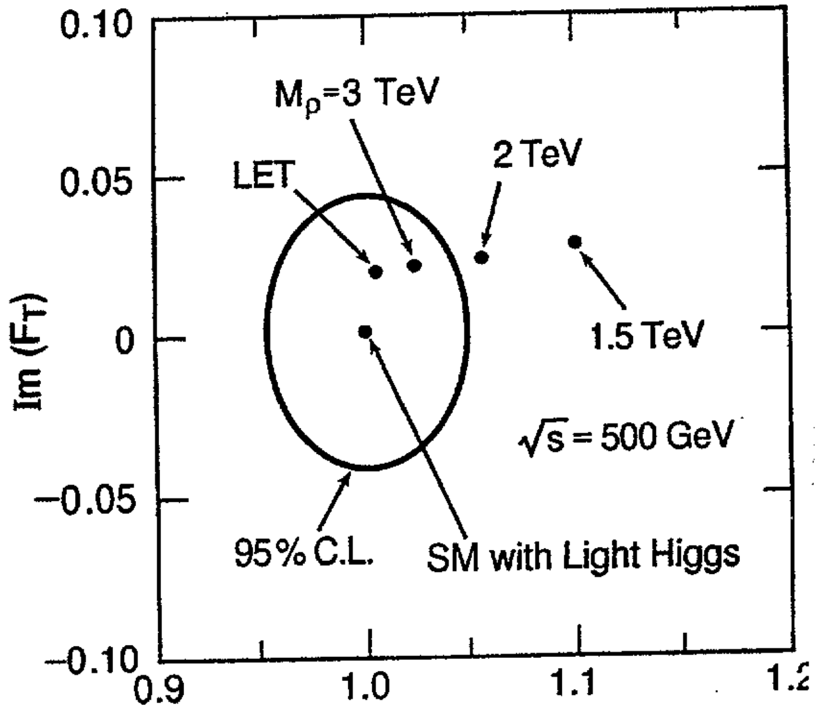
$M_{\rho_T} \approx 1.5$ TeV

SIGNAL 6.7σ

LET POINT
CAN BE EXCLUDED
> 95% CL

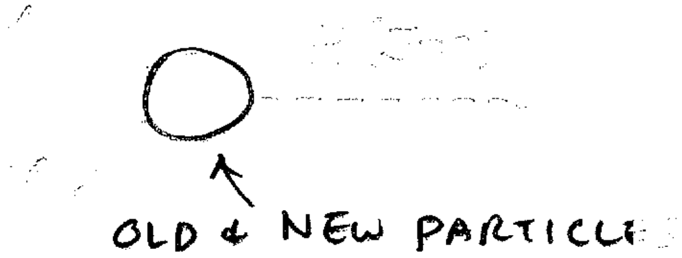
SIGNAL 4.5σ


0.2
0.1
0
–0.1
–0.2
0.9
1.0
1.1
1.2
1.3
1.4
Im (F$_T$)
Re(F$_T$)
LET
3 TeV
4 TeV
M$_\rho$ = 6 TeV
SM with Light Higgs
10-94
7820A2


0.10
0.05
0
–0.05
–0.10
0.9
1.0
1.1
1.
Im (F$_T$)
M$_\rho$=3 TeV
LET
2 TeV
1.5 TeV
$\sqrt{s}$ = 500 GeV
95% C.L.
SM with Light Higgs

$\gamma\gamma$ OPTION

MAIN PHYSICS



γ- PORARIZATION

$\Rightarrow$ SELECT
J = 0

J = 2

$$= \sqrt{s_{\gamma\gamma} / s_{e^+e^-}}$$

$\sqrt{s} = 150$ GeV

SM

$\mathcal{L} \simeq 10\ fb^{-1}/yr$

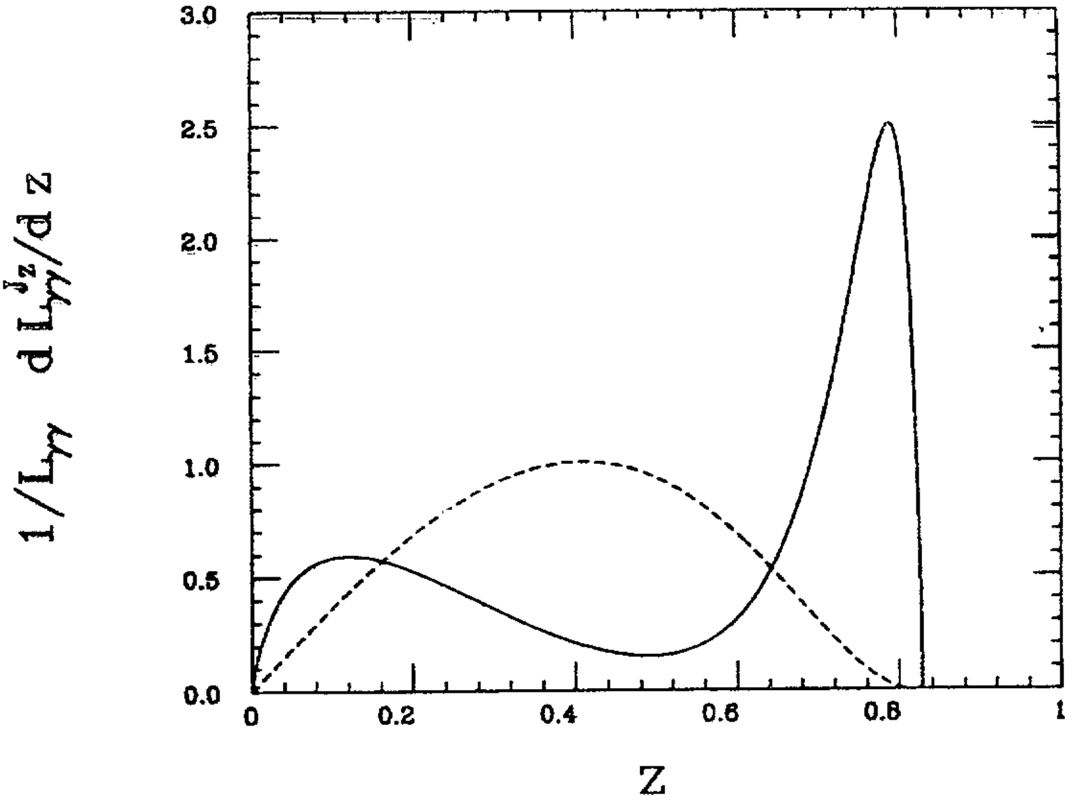
$\Downarrow$

~ 340 HIGGS

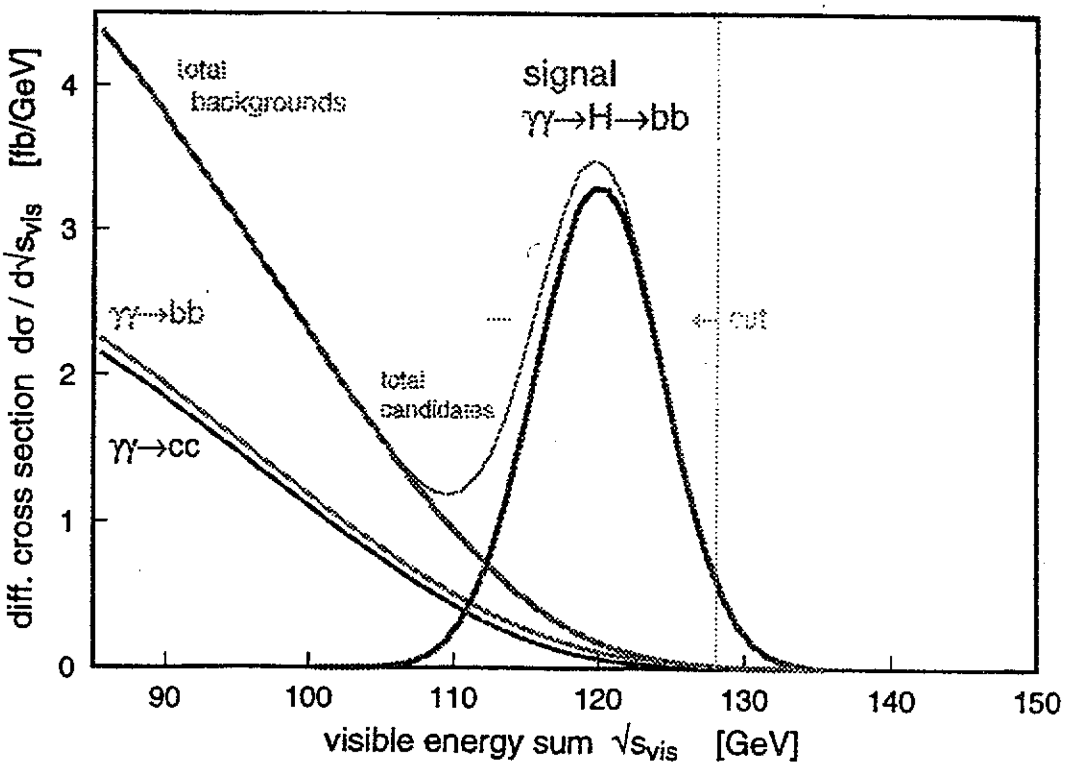
~ 10% BKG

$\varepsilon_{bb} \simeq 0.4$

$\varepsilon_{cc} \simeq 0.02$



1/L_γγ d L_γγ^Jz/d Z
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
0.2
0.4
0.6
0.8
1
Z



diff. cross section dσ / d√s_vis [fb/GeV]
4
3
2
1
0
total backgrounds
signal
γγ→H→bb
γγ→bb
γγ→cc
total candidates
← cut
90
100
110
120
130
140
150
visible energy sum √s_vis [GeV]

LC DETECTORS

1) TAKE FULL ADVANTAGES OF e^+e^- COLLISIONS

EVENT RATE.

FULL RECONSTRUCTION OF EVENTS WITH BEAM ENERGY CONSTRAINT.

2) USE TECHNOLOGIES DEVELOPED FOR LHC DETECTORS

RADIATION HARD DEVICES.

FAST READOUT ELECTRONICS.

EARLY STUDIES IN '80 TH
LEP OR SLD DETECTOR PERFORMANCE
MIGHT BE OK FOR LC EXP'TS.
1992 JLC-1 REPORT PROPOSED
MUCH BETTER DETECTOR FOR HIGGS.
1997 CDR DESY / ECFA STUDIES
1997 ZDR NLC STUDIES

DETECTOR CONCEPT IS DRIVEN BY

YSICS

Zh b-TAG, c-TAG
RECOIL MASS RESOLUTION
JET-JET MASS RESOLUTION

SUSY MISSING P_T
ISOLATED γ'S etc. etc.

HNOLOGY

VERTEX DETECTORS
FAST READ OUT
[DETECTOR TECHNOLOGY MAY NOT BE THE PRIMARY ISSUE FOR e^+e^- EXP'TS.]

③ COLLIDER DESIGN, IR

BUNCH TRAIN STRUCTURE
BACKGROUND AT IR REGION

④ COST

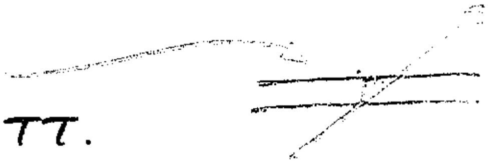
VERTEX DETECTOR

ESSENTIAL FOR b-TAG. ($h^0 \rightarrow b\bar{b}$)
c-TAG.

TECHNICAL CHALLENGES [illegible]

1) SMALLEST POSSIBLE $r_{\text{INNER LAYER}}$
   e^+e^- PAIR BKG ↔ $\vec{B}$ FIELD
   (DETECTOR CONCEPT)

2) THINNEST POSSIBLE LAYERS
   RESOLUTION
   MULTIPLE SCATT.

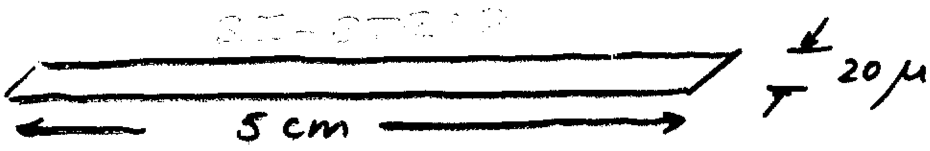


3) LARGE RADIAL SPACING
   NUMBER OF LAYERS
   ⇒ STAND ALONE TRACKING

4) MAXIMUM POSSIBLE $\cos\theta$ COVERAGE

5) FAST READOUT

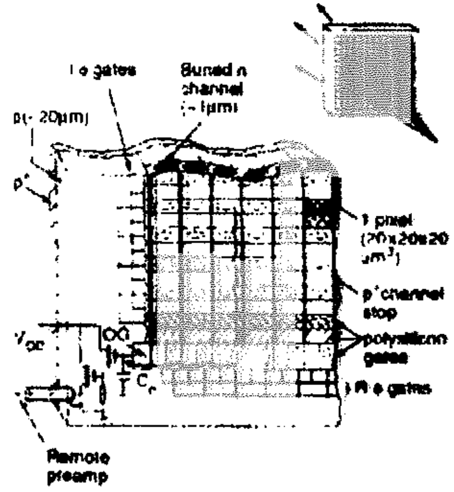
VTX DETECTORS ARE [illegible]
BY OCCUPANCY.



$1\ mm^2$

PIXEL DETECTORS

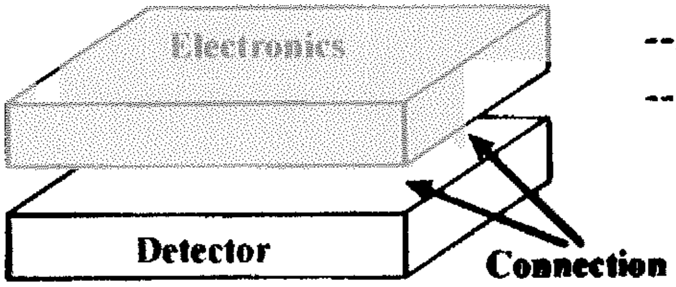
CCD



--> Imaging
--> High Energy Physics (SLD)

Art

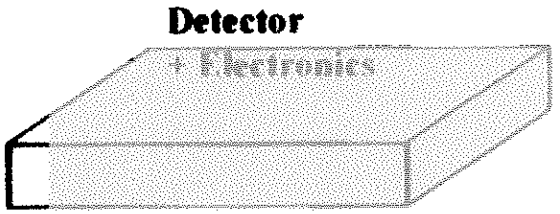
hybrid



--> High Energy Physics
 (DELPHI, ...)

n

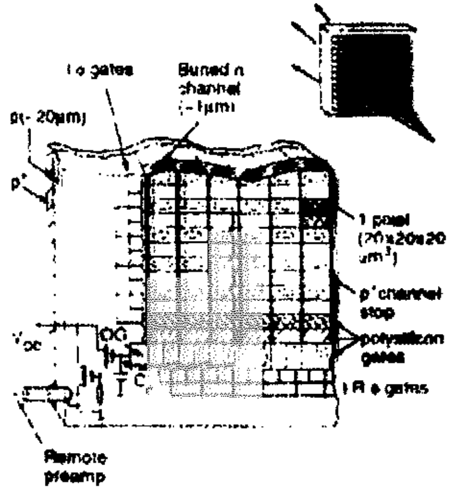
--> High Energy Physics
--> Complex technology



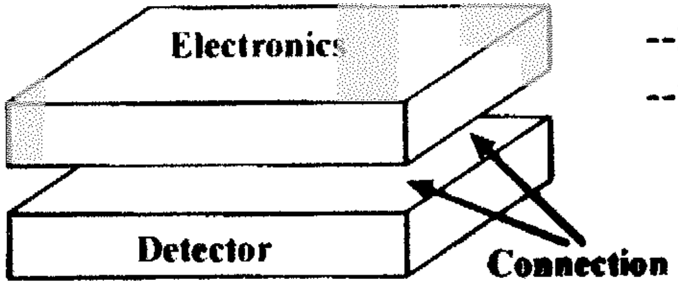
--> Imaging
--> Standard VLSI Technology

PIXEL DETECTORS

CCD

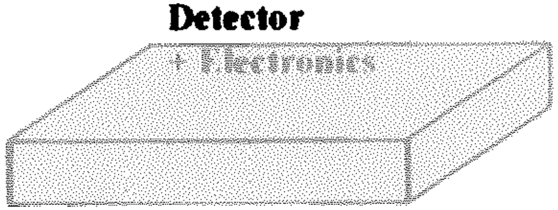


--> Imaging
--> High Energy Physics (SLD)



--> High Energy Physics (DELPHI, ...)

--> High Energy Physics
--> Complex technology



--> Imaging
--> Standard VLSI Technology

CCD (CHARGE-COUPLED DEVICE)

EXPERIENCE
@ SLD

307 M PIXELS

0.4 % X_0 / LAYER

$\sigma_{POINT} \simeq 3.5 \mu$
(BOTH ϕ, z)

THICKNESS
GOAL $\simeq$ 0.12 % X_0 / LAYER

RADIATION HARDNESS
QUITE ROBUST AGAINST $e^{\pm}, \gamma$

FOR HADRONIC BKG.
OK UP TO $\sim 10^{10}$ n/cm^2

CTI (CHARGE TRANSFER INEFFICIENCY)
$< O(10^{-5})$ REQUIRED

ex. $(1 - 5\times10^{-4})^{1024} = 0.59$!

OF SHIFTS
(512 × 512 PIXELS)

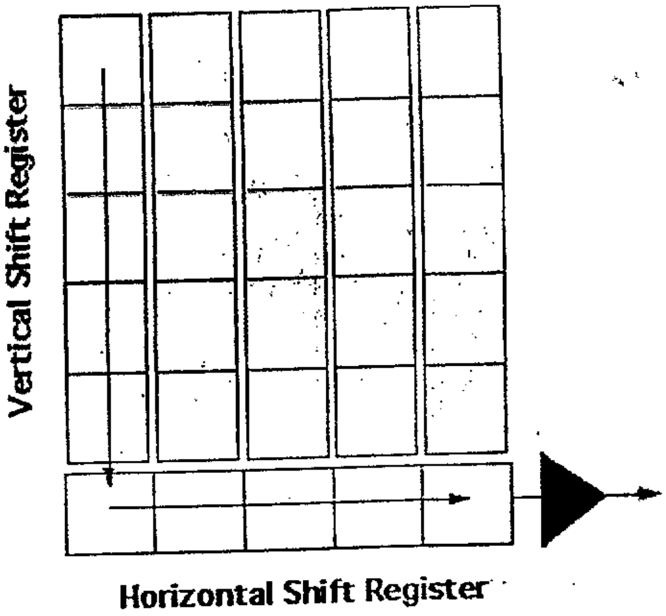
CTI (TEMPERATURE, READ OUT TIME)

READ OUT TIME

JLC / NLC [illegible]

$\sim$ 10 msec INTERVAL

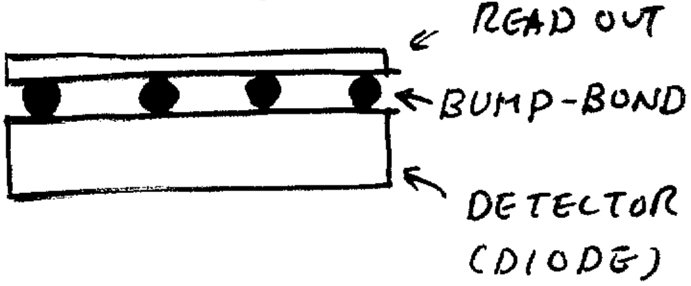
CCD



APS (ACTIVE PIXEL SENSOR)

HYBRIDE APS

ATLAS, CMS, ...



RADIATION HARD

S/N IS GOOD

THICKNESS

ex. ALICE 1.26% X_0

PIXEL SIZE

O(100) μm × O(100) μm

MONOLITHC APS

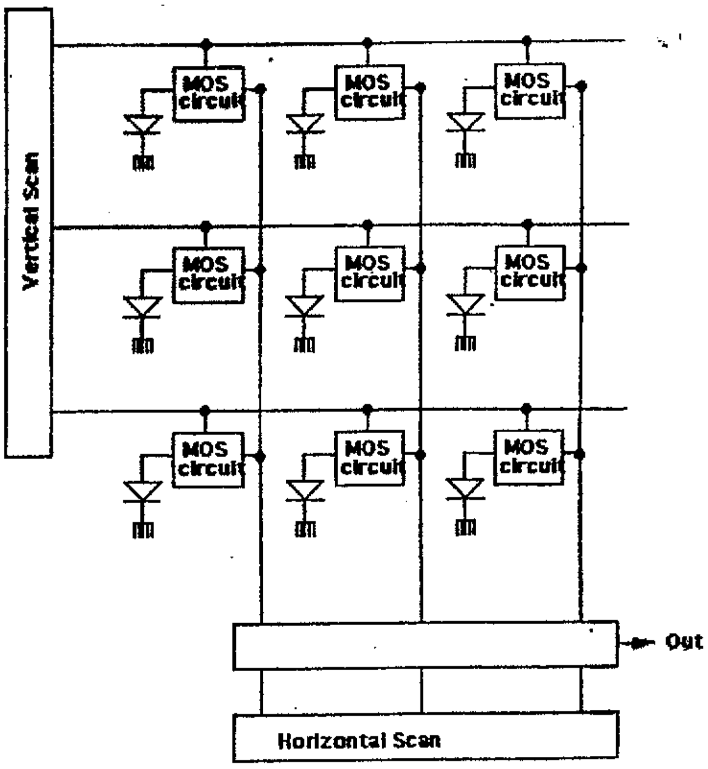
STANDARD VLSI TECHNOLOGY
USING LOW RESISTIVITY SI

SPECIAL PROCESS ON HIGE RESISTIVITY
IS NOT NEEDED

GOOD EFFICIENCY FOR MIPS

LARGE SIZE DETECTOR }
READ OUT
NEED TO BE DEMONSTRATED

MOS Sensor


Vertical Scan
MOS circuit
MOS circuit
MOS circuit
MOS circuit
MOS circuit
MOS circuit
MOS circuit
MOS circuit
MOS circuit
Out
Horizontal Scan

CENTRAL TRACKERS

GENERAL ISSUES

1) P_T RESOLUTION FOR HIGH $P_\perp$ TRACKS
(e.g. $HZ \to b\bar{b}\,\ell^+\ell^-$)

$$\frac{\sigma_{p_\perp}}{p_\perp} \propto \frac{\delta}{\sqrt{N}} \frac{p_\perp}{BL^2}$$

B, L ⇐ GENERAL DETECTOR CONCEPT.

δ ⇐ v_D, DIFFUSION (FOR GAS CH.)

N ⇐ PATTER RECOGNITION

$\sigma(\frac{1}{p_\perp})$	8×10^{-4}	2×10^{-4}
$P_\perp = 250$ GeV	5σ CHARGE SEPARATION	5% MOMENTUM RESOLUTION

2) LOW MOMENTUM TRACKS IN JETS

MAJORITY OF TRACKS $P_\perp < 10$ GeV

MULTIPLE SCATTERING IS DOMINANT

3) PARTICLE·ID, RECONSTRUCTION

dE/dx FOR e/π K/π SEPARATION

D-MESON RECONSTRUCTION $K^0 \to \pi\pi$
[illegible]

4) FORWARD TRACKING

5) INTERMEDIATE TRACKER

LINKS TRACKS BETWEEN VTX AND CT.
IMPORTANT FOR PATTERN
RECOGNITION EFFICIENCY.

⇒ CHOICE OF THE DEVICE ?

6) BUNCH I.D FOR JLC AND NLC

BUNCH SEPARATION = 2.
POINT RESOLUTION $\sim \sqrt{v_D}$ (NOT $\sim v_D$)

⇒ FAST v_D IS BETTER

$\sigma_{point} \simeq 200\,\mu$, $v_D = 5$[illegible] , [illegible] 100

$\sigma_t = \frac{200\,\mu}{\sqrt{100}} \frac{1}{5?}$ [illegible] $\simeq 0.4$ ns $\ll$ [illegible]

FOR GOOD SPACE RESOLUTION
SMALL LORENTZ ANGLE
SMALLER v_D MIGHT BE BETTER.

DISCUSSIONS ON

B SOLENOIDAL MAGNETIC FIELD

L EFFECTIVE RADIAL LENGH

⇒ LATER
IN CALORIMETRY.

CENTRAL TRACKERS FOR LCs

(K. Riles Keystone)

	JLC-1	ECFA-CDR	Snowmass 96
TYPE	JET CELL LARGE RADIUS	TPC UPGRADED ALEPH, DELPHI	COMPACT SI. FINAL Q OUTSIDE OF DETECTOR
Rout	2.3 m	1.6 m	0.5 m
$\|\vec{B}\|$	2 T	3 T	4 T
δ POINT	100 μ ($\sigma_z = 2\,\mathrm{mm}$)	140 μ	10 μ
NSAMPLE	56 (axial) 49 (stereo)	118	10 ($r\phi$) 5 (z)
$\sigma(\frac{1}{p_\perp})$ (C.T)	1×10^{-4}	3×10^{-4}	6×10^{-4}
(VTX. BEAM CONSTR)	5×10^{-5}	6×10^{-5}	1×10^{-4}
COMMENTS	$L = 4.6\,\mathrm{m}$ GRAV. SAG TESTED $v_D = 10\,\mu/\mathrm{ns}$ 2 track sep. $\sim 1\,\mathrm{mm}$ TESTED	MAX DRIFT TIME $= 50\,\mu\mathrm{s}$ ELECTRON AVALANCHE MANY IDEAS WIRES, GEM, MSGC, ...	$34\,\mathrm{m}^2$ silicon PATTERN RECOG. ? BUNCH ID ???

CALORIMETERS

1) ENERGY FLOW MEASUREMENTS

- CALORIMETRY BASED EXPERIMENTS

⇒ LOW B-FIELD + μ TOROID OUTSIDE TO AVOID CHARGED PARTICLE SPREADING FROM JET-CORE AND INCLINED INCIDENT ANGLE AT CALORIMETER SURFACE.

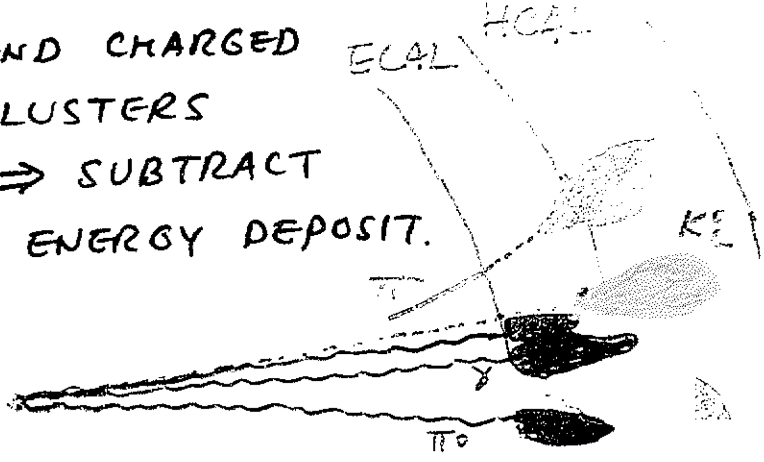
- TRACKING + CALORIMETRY COMBINED.

⇒ NEED HIGH B-FIELD

TRUSTING MOMENTUM MEASUREMENT FOR CHARGED PARTICLES

SEPARATE THEM FROM JET-CORE BY B-FIELD AND ELIMINATE CLUSTERS DUE TO THE CHARGED PARTICLES.

IF OVERLAP OF NEUTRAL CLUSTER AND CHARGED PARTICLE CLUSTERS OVERLAP ⇒ SUBTRACT EXPECTED ENERGY DEPOSIT.



⇒ COMPENSATION

$$\left(\frac{\gamma \text{ SIGNAL}}{\pi^{\pm} \text{SIGNAL}} \simeq 1 \right)$$

2) RESOLUTION

- BALANCE BETWEEN TRACKER MOMENTU RESOLUTION AND CAL RESOLUTION

δM_{jj} IS DOMINATED BY CAL RESOLUTION FOR $\sigma(\frac{1}{p_\perp}) \lesssim 10^{-4}$, $\frac{\sigma_E}{E} \sim \frac{15\%}{\sqrt{E}}$ (E

$$Zh \quad h \to b\bar{b}, \quad Z \to \nu\bar{\nu}$$

$m_h = 80\,\text{GeV}$

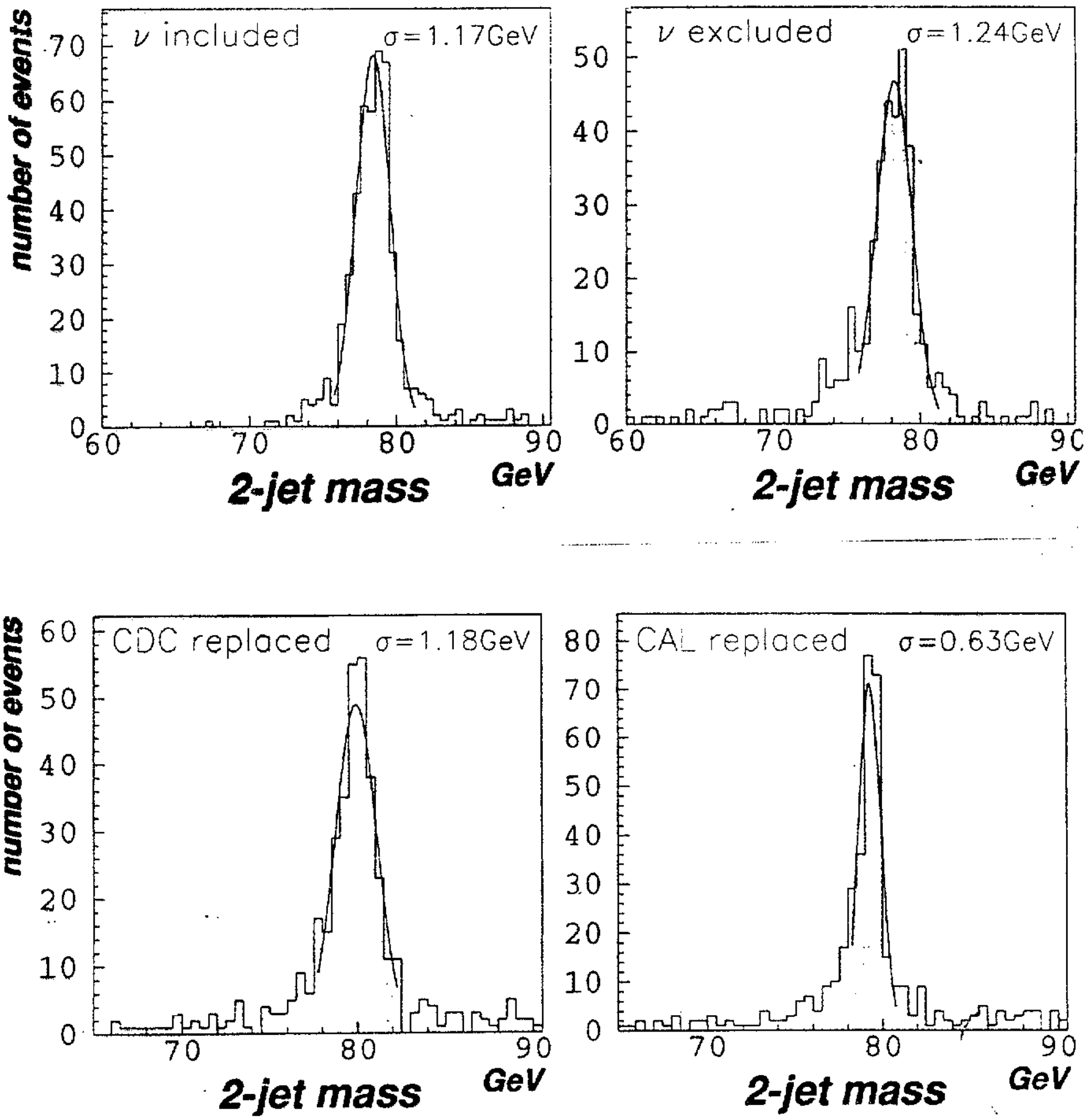
NOMINAL
CONDITION

IDEAL TRK.

IDEAL
CAL.

WITH
charged
particle
4-momentum
vector

WITH
γ, e 4-vector


ν included
σ=1.17GeV
ν excluded
σ=1.24GeV
CDC replaced
σ=1.18GeV
CAL replaced
σ=0.63GeV
number of events
2-jet mass
GeV
0
10
20
30
40
50
60
70
80
60
70
80
90

- ISOLATED 50 GeV e^-

  $\Delta P/P \simeq 0.5\%$ $\Delta E/E \simeq 1.4\%$

  $(\sigma(\frac{1}{p}) \simeq 10^{-4}$, $\sigma_E/E \simeq 10\%/\sqrt{E})$

- HCAL RESOLUTION

  $\frac{\sigma_E}{E} \leq \frac{40\%}{\sqrt{E}}$ NEEDED ?

  COMPENSATION NEEDED ?

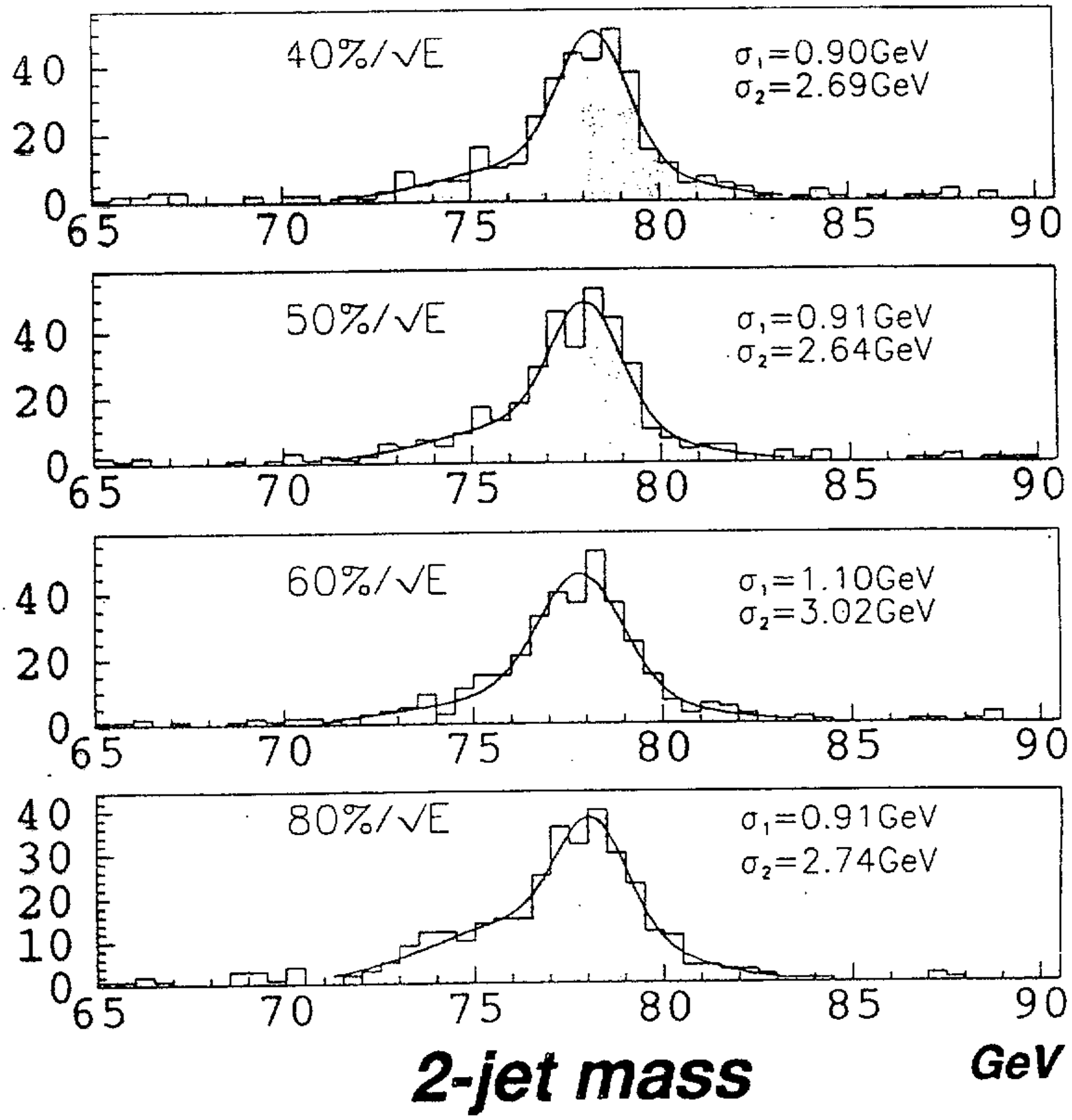
  THIN SCINT. LAYER → LOW PHOTON

  → HIGH GAIN PHOTO-DETECTOR (

  COIL SHOULD BE OUTSIDE OF HCAL ?

  SUPERCOND. COIL 30 cm CH_2 → [illegible]

Y. Fujii


40%/√E
σ₁=0.90GeV
σ₂=2.69GeV
50%/√E
σ₁=0.91GeV
σ₂=2.64GeV
60%/√E
σ₁=1.10GeV
σ₂=3.02GeV
80%/√E
σ₁=0.91GeV
σ₂=2.74GeV
0
10
20
30
40
65
70
75
80
85
90
2-jet mass
GeV

CALORIMETERS IN ACTUAL EXP'T

1) LIQUID ARGON — Uranium

SLD, H1, DØ, (GEM), ATLAS

EM EM EM

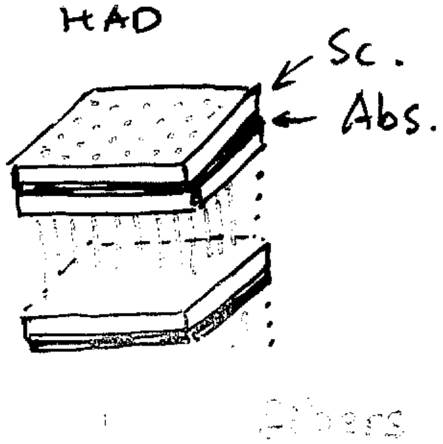
HAD HAD HAD CE

- CRYO. IS NEEDED.
- FIN GRANULARITY ⇒ SOFTWARE WEIGHTING COMPENSATION (H1)
- HARD TO REACH DESIGN RESOLUTION.
- TYPICALLY

$$\sigma_E/E \simeq 10\%/\sqrt{E} \qquad \sigma_E/E \simeq 50\%/\sqrt{E}$$

EM HAD

2) SHASHLIK



PHENIX, HERAB, LHCB

- COMPACTNESS IN DEPTH
- ASSEMBLY FOR LARGE COLLIDER DETECTOR ?
- FRAGILE WLS (TORTION, FRICTION)
- TYPICALLY

$$\sigma_E/E \lesssim 10\%/\sqrt{E} \text{ for EM}$$

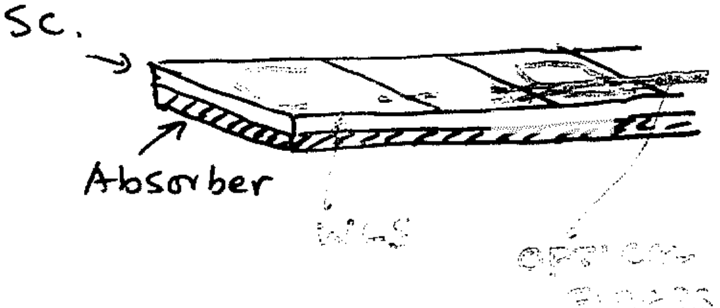
3) TILE FIBER

CDF, STAR, (SDC), ATLAS, CMS

EM EM EM HAD HA

Sc. Barrel Barrel [illegible]

- COMMONLY USED FOR HADRON COLLDER EXP'TS



- EASY TO VARY PAD SIZE/SHAPE
- LONG READ OUT FIBER
- TYPICALLY

  $\sigma_E/E \simeq 15\%/\sqrt{E}$ EM

  $60\%/\sqrt{E}$ HAD

- LOW COST FOR [illegible] (~SHASHLIK)

4) CRYSTALS FOR ECAL

CMS L3

$PbWO_4$ BGO

- EXCELLENT ECAL RESOLUTION
- LONGITUDINAL SEGMENTATION DIFFICULT
- NOT SO FAST AS PLASTIC SCINTILLATORS

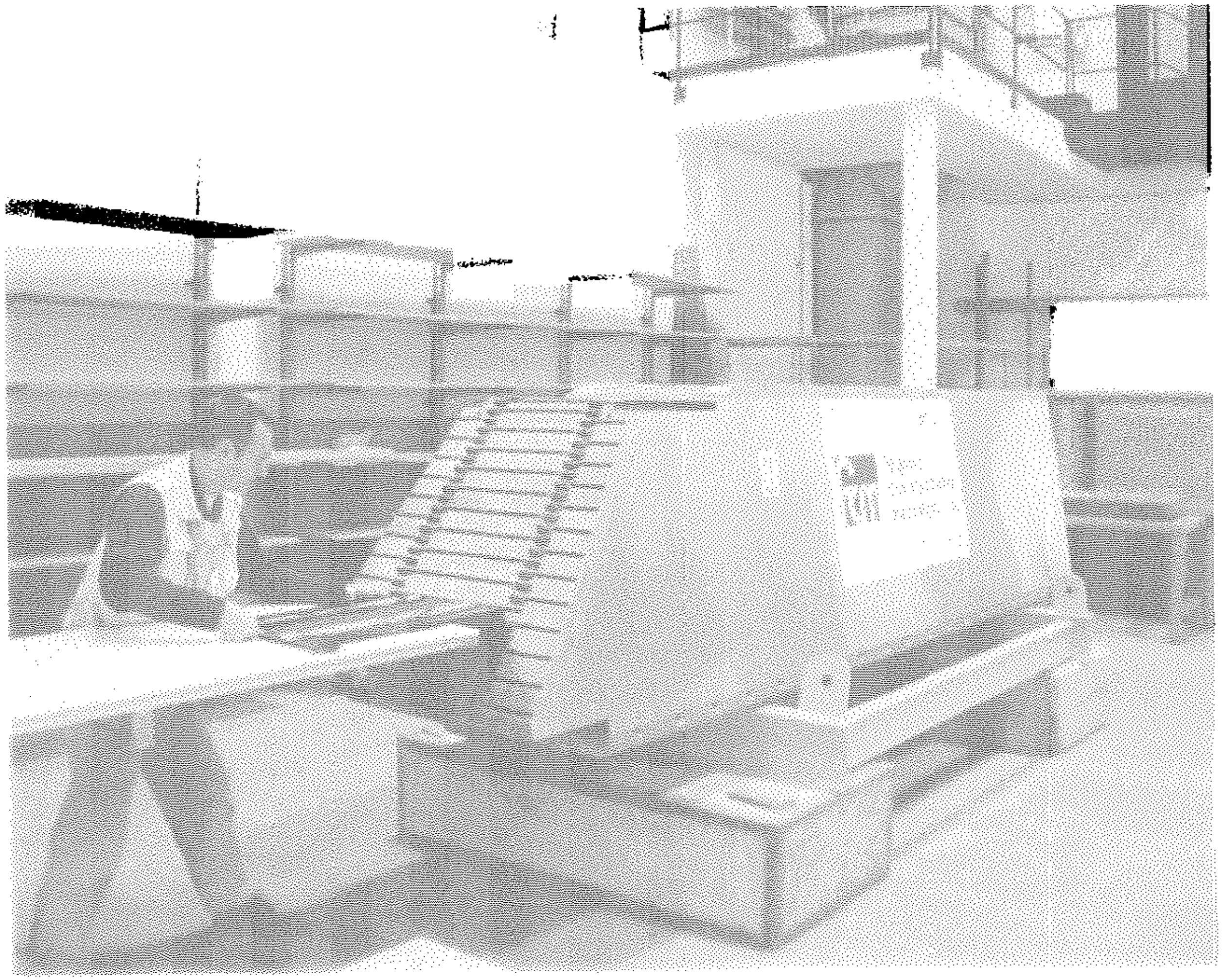
  RISE TIME IS OK → BUNCH ID

- TO HAVE EXCELLENT RESOLUTION

  { TEMPERATURE CONTROL

  LIGHT YIELD ~ 2% / 1°C $PbWO_4$

PPP1



BEAM TESTS (JLC)

1) LOW ENERGY BEAM TESTS AT KEK
   TILE-FIBER CAL $E \lesssim 4\,\mathrm{GeV}$
2) PLANNING BEAM TEST @ FNAL FALL '99
   $5 < E < 200\,\mathrm{GeV}$

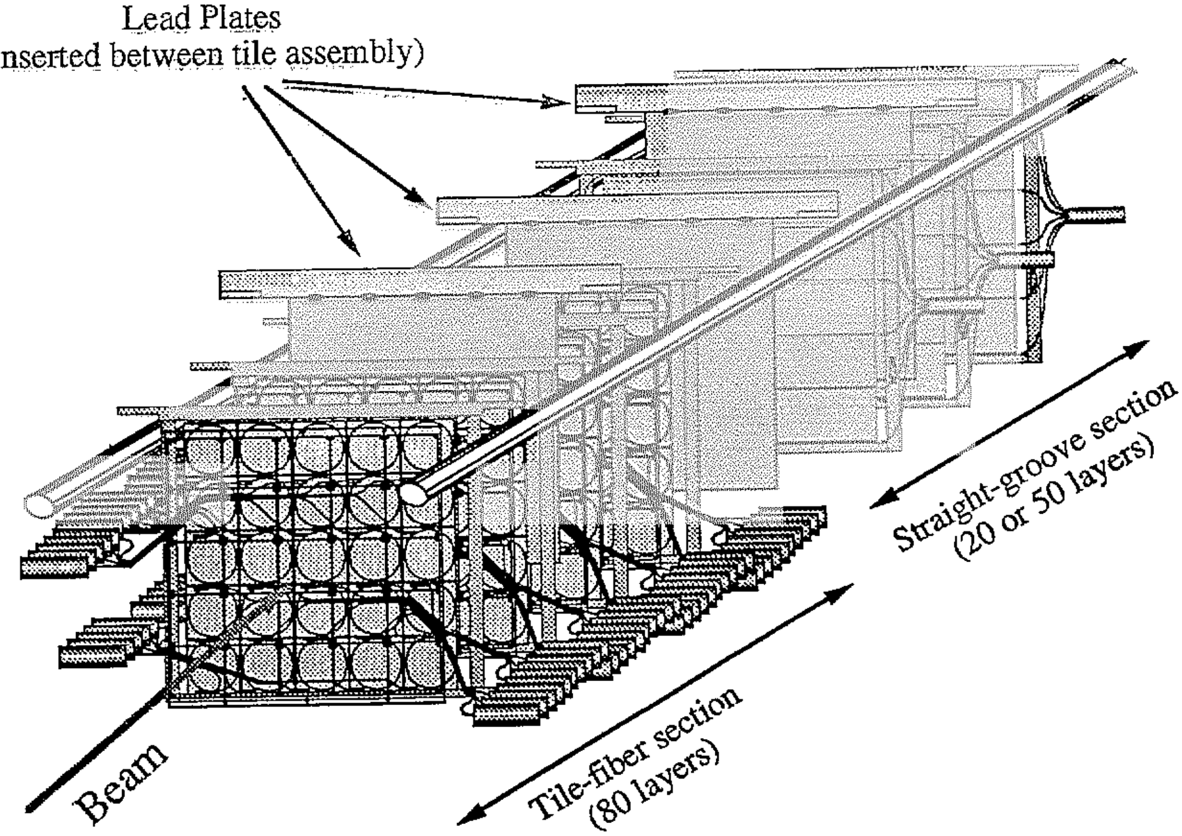
RESOLUTION

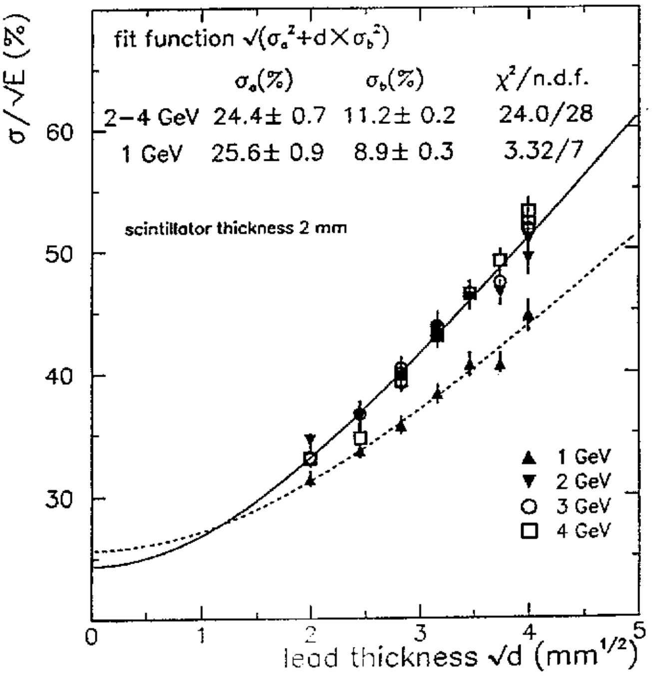
COMPENSATION

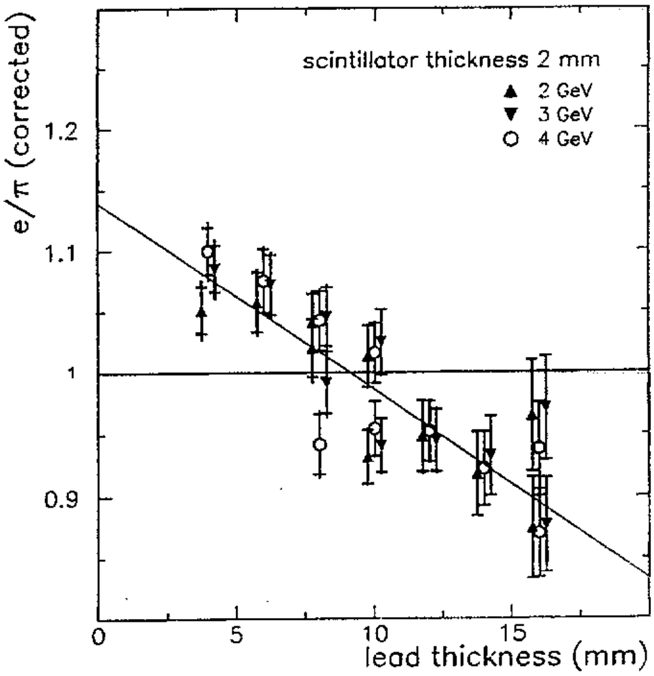
$Sc : Pb = 2\,\mathrm{mm} : 8\,\mathrm{mm}$

↙

$Sc : Pb = 2\,\mathrm{mm} : 4\,\mathrm{mm}$
$\sim 33\% / \sqrt{E}$


Lead Plates
(inserted between tile assembly)
Straight-groove section
(20 or 50 layers)
Tile-fiber section
(80 layers)
Beam


fit function $\sqrt{(\sigma_a^2+d\times\sigma_b^2)}$
σ_a(%) σ_b(%) χ^2/n.d.f.
2−4 GeV 24.4± 0.7 11.2± 0.2 24.0/28
1 GeV 25.6± 0.9 8.9± 0.3 3.32/7
scintillator thickness 2 mm
▲ 1 GeV
▼ 2 GeV
○ 3 GeV
□ 4 GeV
$\sigma/\sqrt{E}$ (%)
30
40
50
60
0
1
2
3
4
5
lead thickness $\sqrt{d}$ (mm$^{1/2}$)


scintillator thickness 2 mm
▲ 2 GeV
▼ 3 GeV
○ 4 GeV
e/π (corrected)
0.9
1
1.1
1.2
0
5
10
15
lead thickness (mm)

INTERACTION REGION MACHINE RELATED BACKGROUND

1) DESIGN OF THE LAST Q-MAGNET

- PRECISION OF THE FIELD INSIDE THE MAGNET. • MECHANICAL STABLIZATION • POSITION • SIZE
- COMPENSATION OF SOLENOID FIELD (NORMAL MAGNET)

⇒ BACKGROUND CONDITION

⇒ FORWARD COVERAGE

2) SYNCHROTRON RADIATION FROM BENDING- AND Q-MAGNETS

- SR FROM UPSTREAM ~100 m AWAY FROM IP.

  MASK 20 cm THICK W

  ⇒ REDUCE 1~2 MeV γ BY 2×10 [illegible]

- SR FROM FINAL Q-MAGNETS

  OPTIMIZE THE OPTICS OF THE FINAL FOCUS SYS.

MASK FOR TESLA

5) SECONDARY PHOTONS, NEUTRONS

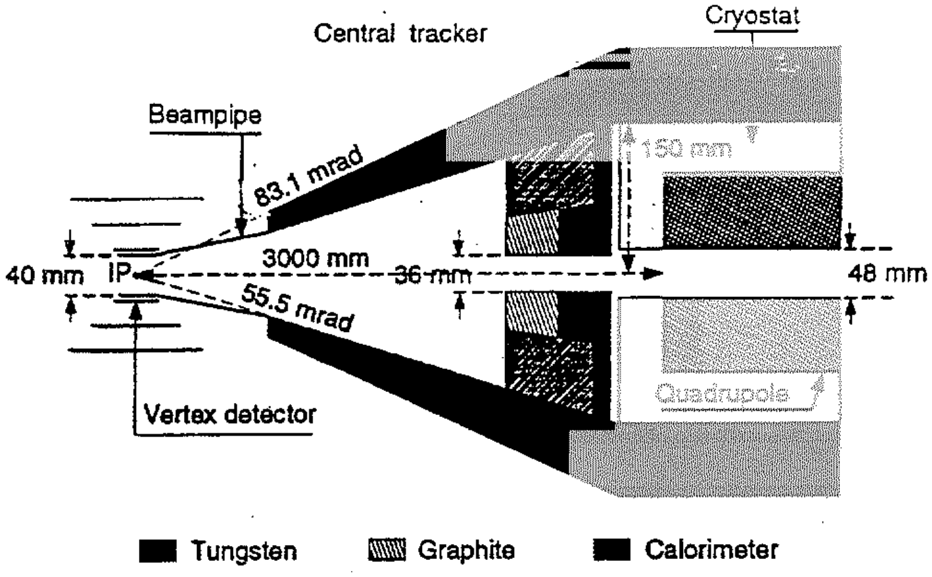
SYNCHROTRON RADIATION
BACK SCATTERED AT Q-MAGNET
FACE ⇒ MASK

PHOTO PRODUCTION NEUTRONS
THROUGH NUCLEAR GIANT
RESONANCE $E_n \sim 1.5$ MeV ⇒ [illegible]

⇒ ABSORBED WITH H-RICH
MATERIAL

NEUTRONS ARE ALSO FROM
BEAM DAMP OR EVERYWHERE.

⇒ CAREFUL DESIGN OF
SHIELD, BEAM DAMP.


Central tracker
Cryostat
Beampipe
83.1 mrad
150 mm
40 mm
IP
3000 mm
36 mm
48 mm
55.5 mrad
Quadrupole
Vertex detector
Tungsten
Graphite
Calorimeter

6) MINIJETS (HADRONIC TWO PHOTON PROCESSES)

- HUGE CROSS SECTION

  $\sigma \simeq 30-60\ nb$ $\left(\sqrt{s} = 300\ GeV\quad M_{\gamma\gamma} > 2\ GeV\right)$

- OVERLAP PROBABILITY

  JLC-C, X NLC-X

  $$\frac{7 \times 10^{33}\ cm^{-2}\ s^{-1}}{100 \times 100} \sim 0.7 \times 10^{-3}\ nb\ / bunch$$

  $$\sigma \cdot \mathcal{L}_{bunch} \sim 0.02 - 0.04$$

  TESLA HIGH $\mathcal{L}$

  $$\frac{30 \times 10^{33}\ cm^{-2}\ s^{-1}}{2800 \times 5} \sim 2 \times 10^{-3}\ nb\ / bunch$$

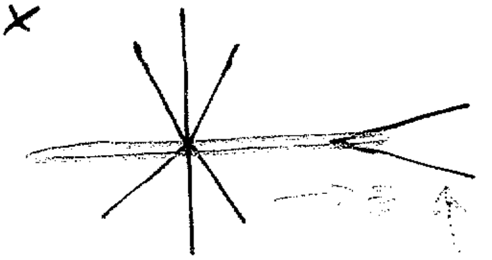
  $$\sigma \cdot \mathcal{L}_{bunch} \sim 0.06 - 0.12$$

- FORWARD GOING JETS

  P_T IS SMALL BUT $P_{\parallel}$ IS NOT SMALL.

  MIGHT AFFECT $|\cos\theta_{MISS.}|$, P_Z CUTS

- VERTEX



"Belle, Babar events" or "LHC events"

SUMMARY OF DETECTOR ISSUES

FOR LHC EXPERIMENTS, REQUIREMENTS OF FAST DETECTOR RESPONCE AND RADIATION HARDNESS CAN LIMIT DETECTOR TECHNOLOGIES.

FOR e^+e^- COLLIDER EXPERIMENTS
PHYSICS IS WELL DEFINED,
BACKGROUND IS WELL UNDERSTOOD,

[illegible]ECISION OF THE MEASUREMENTS
[illegible]E FOR e^+e^- LC EXPERIMENTS
[illegible]CH HIGHER THAN FOR LHC.

REQUIREMENTS SHOULD
[illegible]IED MAINLY FROM THE
WELL DEFINED PHYSICS PROGRAM.

EXCHANGING INFORMATION IN THE WORLD-WIDE LC SOCIETY HELPS TO OPTIMIZE LC DETECTORS.

SUMMARY FOR PHYSICISTS

PHYSICS THRESHOLDS

1) LIGHT HIGGS

$m_h \lesssim 200$ GeV ($\lesssim 130$ GeV MSSM)

$\Rightarrow \sqrt{s} \simeq 200 \sim 300$ GeV

DEFINITELY TESTED & STUDIED

2) TOP PAIR PRODUCTION

$\sqrt{s} \simeq 2m_t \simeq 350$ GeV

KNOWN

3) SUSY

UNKNOWN

$\sqrt{s} \lesssim O(\text{TeV})$

4) NEW STRONG INTERACTION

(if no light Higgs Boson)

UNKNOWN

$\sqrt{s} \sim O(\text{TeV})$

FOR CLIC LINEAR COLLIDER
NEXT THRESHOLD

$\sqrt{s} \lesssim$ few TeV

THESE SCIENTIFIC MOTIVATIONS (HIGGS + TOP) ARE ENOUGH TO JUSTIFY THE AGGRESSIVE SCHEDULES OF JLC, NLC AND TESLA.

ALSO, e^+e^- LC SHOULD BE COMPETITIVE / COMPLEMENTARY LHC.

THE IMPORTANT STEP IS TO DESIGN THE 1ST PHASE e^+e^- LC ON TIME WITH (ALMOST) ESTABLISHED TECHNOLOGIES.

RELATIVELY CHEAP, RELIABLE
STABLE, SIMPLE, EASY OPERATION
RELATIVELY POWER EFFICIENT
⇒ NEXT 3 TALKS

THE NEXT STEP (2ND PHASE) CANNOT BE DEFINED NOW. THRESHOLDS ARE UNKNOWN.

WAIT AND SEE, WHILE ENJOYING THE 1ST PHASE e^+e^- LC.,

LHC PHYSICS RESULTS
HIGHER GRADIENT LC TECHNOLOGY
MUON COLLIDER TECHNOLOGY
⇒ CLIC, μ-COLLIDER TA

PHYSICS SHOULD
BE DONE
STEP BY STEP.

DRIVEN BY
SCIENTFIC MOTIVATION
COLLABORATION / COMPETITION

- LOSE THEOREM

CAN LOSE
EVERYTHING.

(ex. SSC
ITER)

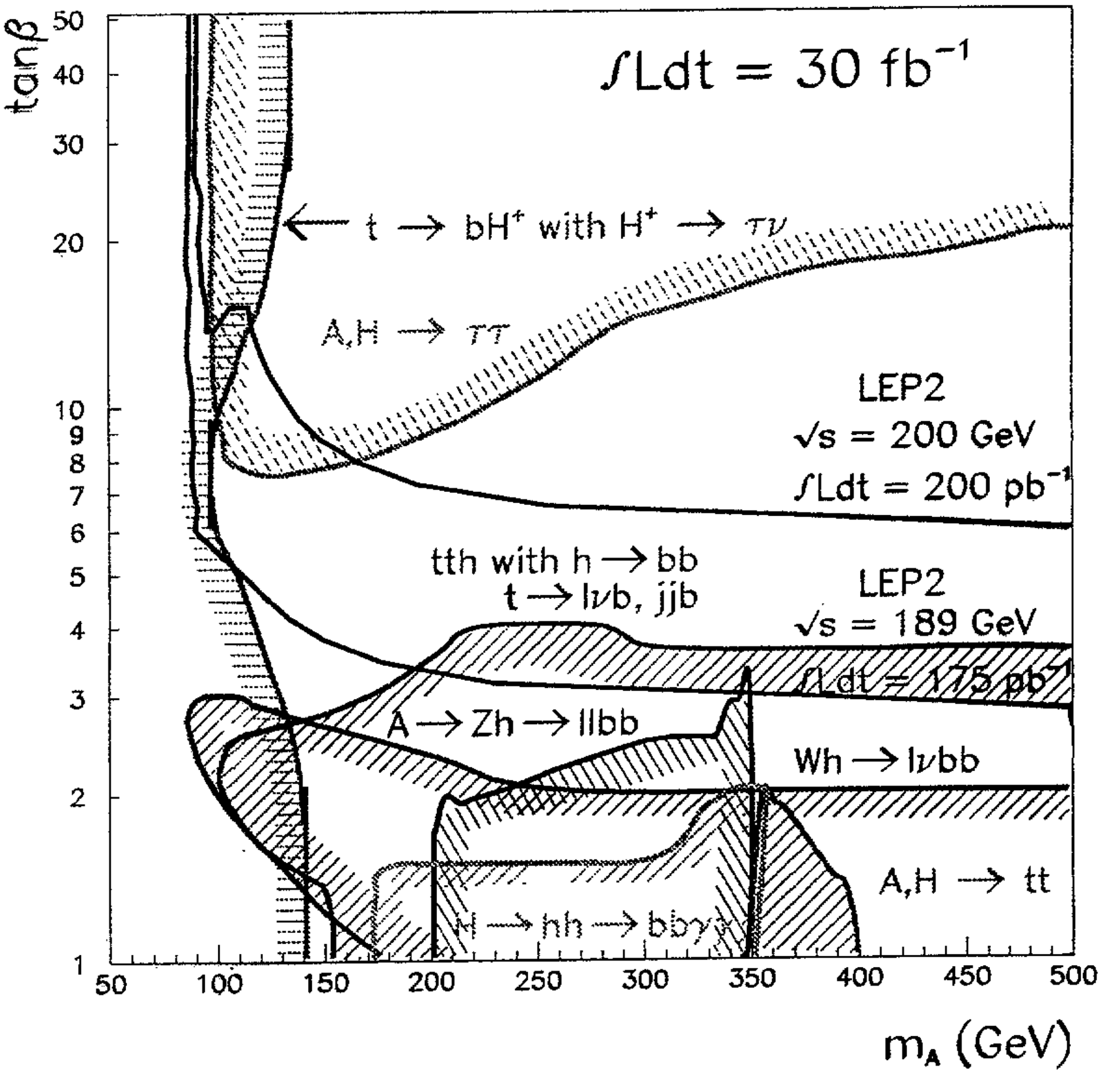


Figure 21-87 The 5σ discovery contour curves in the (m_A, tanβ) plane for the individual channels discussed, assuming an integrated luminosity of 30 fb^{-1} and minimal mixing. Also included are the present LEP200 limit assuming an integrated luminosity of 175 pb^{-1} as well as the expected limit assuming an integrated luminosity of 200 pb-1 at a cms energy of 200 GeV. Presented LEP200 limits courtesy to P. Janot. .

and 21-88 the minimal mixing have been assumed. This is a pessimistic scenario for LHC, since a larger mixing would shift up the lower bound of m_h, thereby increase the discovery potential of LHC. Nevertheless, the overall picture remains the same:

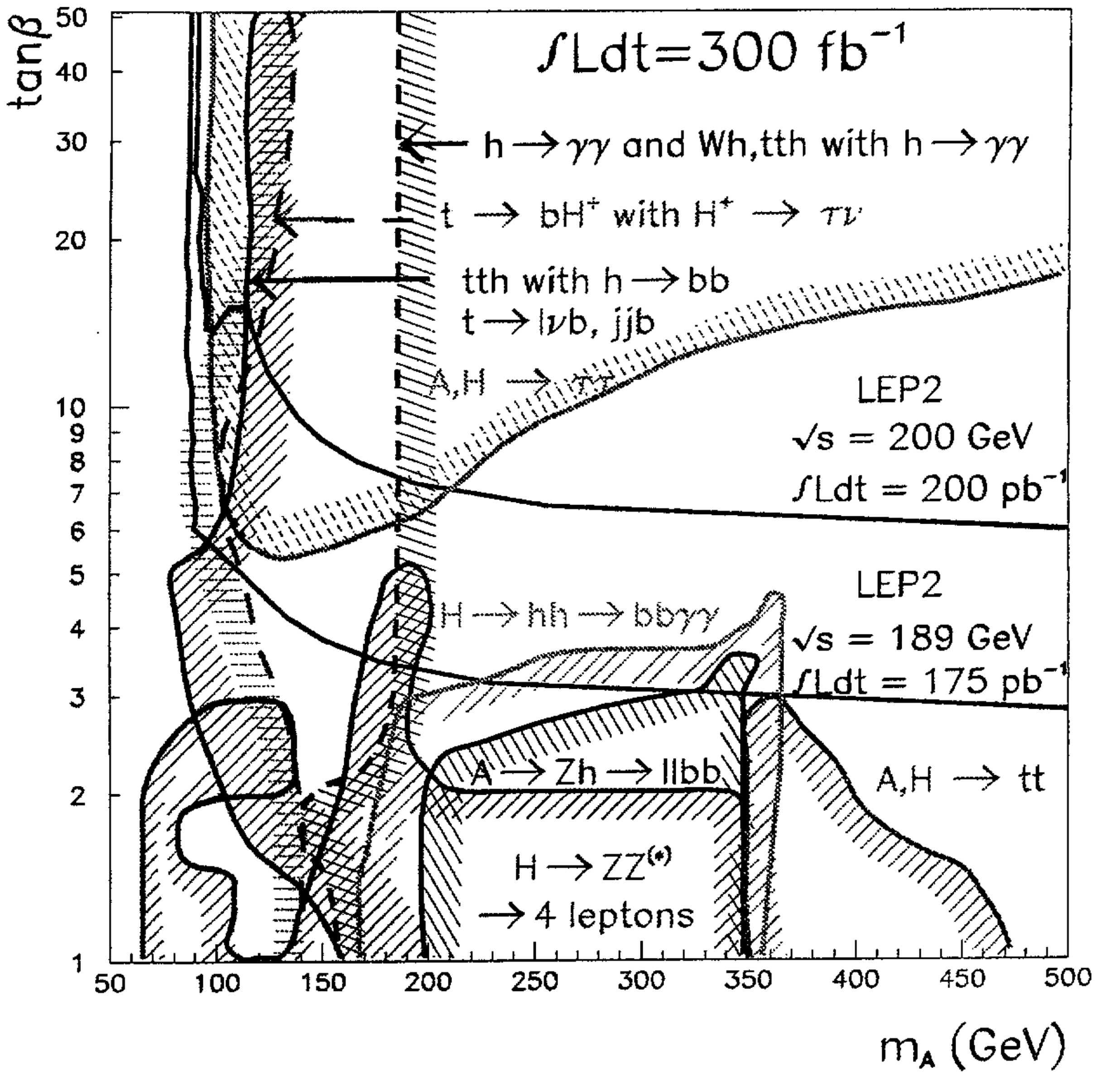
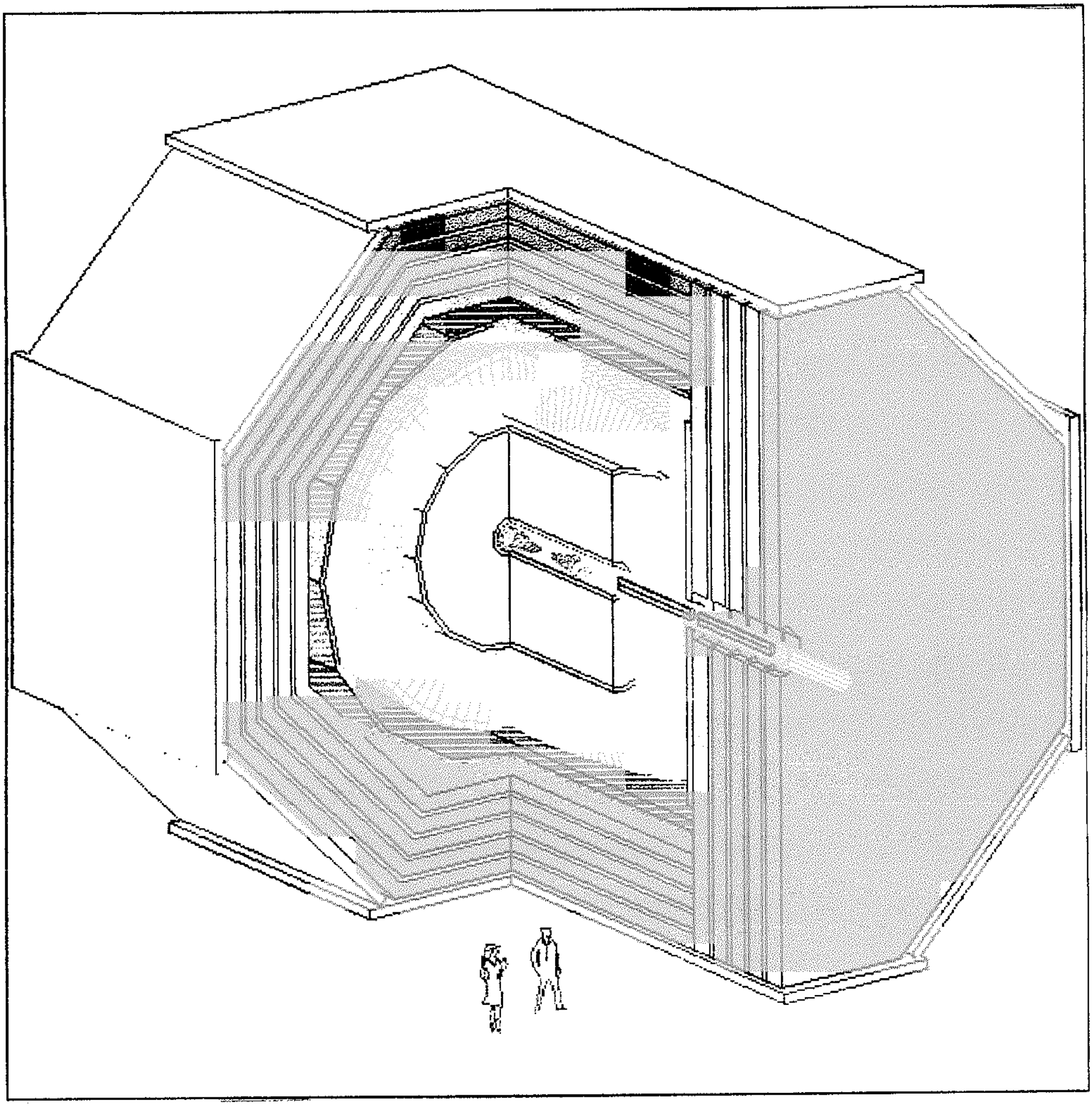
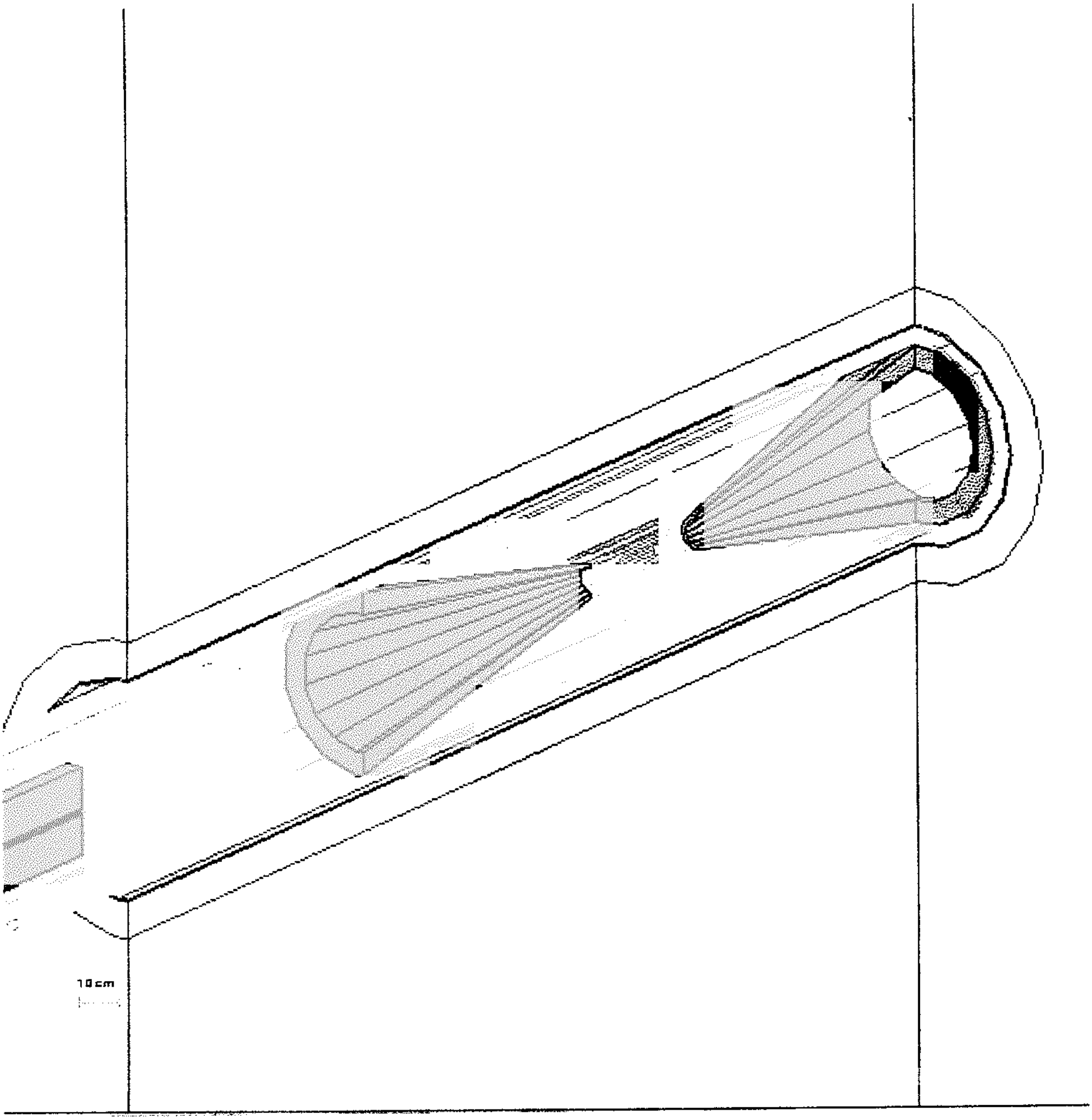


Figure 21-88 The same as **Figure 21-87**, but for **an integrated luminosity of 300** fb^{-1}.

- With a modest integrated luminosity of 30 fb^{-1}, the ATLAS discovery potential covers large fraction of the parameter space. For 80 % to 90 % of the cases the discovery of a Higgs boson would allow for discrimination between the SM case and the MSSM case;




10cm